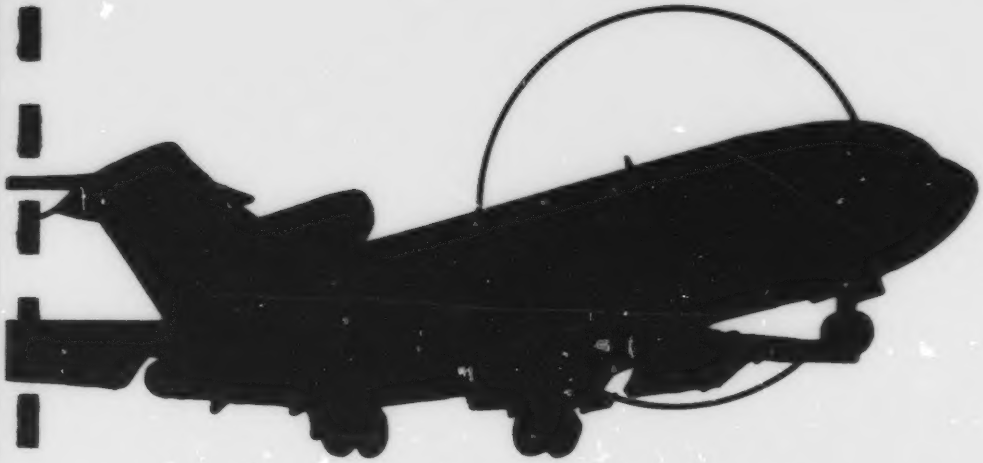
TP 10888E



AIRCRAFT TAKE-OFF PERFORMANCE AND RISKS FOR WET AND CONTAMINATED RUNWAYS IN CANADA

Prepared for
Transportation Development Centre
Policy and Coordination Group
Transport Canada

SYPHER
MUELLER

July 1991

TP 10888E

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Library and Information Centre /
Centre de Documentation (GSCA)
RECEIVED - REÇU LE
JAN 10 1992
Transport Canada / Transports Canada

July 1991

492018

DOII 476230

93-01468/

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LANGUAGE NOTICE

Un sommaire en français de ce rapport est inclus avant la Table de matieres.

Transport Canada Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No. TP 10888E	2. Project No. 7142	3. Recipient's Catalogue No.

4. Title and Subtitle

AIRCRAFT TAKE-OFF PERFORMANCE AND RISKS FOR WET AND CONTAMINATED RUNWAYS IN CANADA

5. Publication Date
July 1991

6. Performing Organization Document No.
88279

7. Author(s) David C. Biggs, Gordon B. Hamilton, Ken D.J. Owen Walter McLeish, L.D. Reid

8. Transport Canada File No.
D1455-203-2

9. Performing Organization Name and Address

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10. DSS File No.
T8200-8-8522

11. DSS or Transport Canada Contract No.

12. Sponsoring Agency Name and Address

Transportation Development Centre
200 Rene Levesque Blvd. West
Suite 601, West Tower
Montreal, Quebec H2Z 1X4

13. Type of Publication and Period Covered
Final

14. Project Officer
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15. Supplementary Notes (Funding programs, titles of related publications, etc.)

16. Abstract

This report documents the results of a study into the risks associated with degraded performance during rejected and continued take-off from wet and contaminated runways. A comprehensive review of world-wide accident and incident data was undertaken to identify the severity of the problem and the factors involved. Runway condition characteristics, the correlation of runway friction test devices with the friction experienced by aeroplanes, and take-off performance estimation on wet and contaminated runways were reviewed. Performance estimates were examined on the basis of the ratio of contaminated versus dry friction. A method is outlined for classifying runway conditions based upon ICAO SARPS, FAA/NASA trials, and the practices of leading countries and airlines. The frequency of wet and contaminated runways in Canada, the likelihood of critical events on the take-off run and the take-off weight distribution were determined. These frequency and probability distributions and runway, weather and aircraft performance data were utilized in a probabilistic analysis of the risk of take-off accidents. A number of counter measures were examined, including the JAR acceptable means of compliance for wet and contaminated runways, and recommendations are given for further work required for effectively including wet and contaminated runway accountability in the take-off performance regulations.

17. Key Words
Aircraft, take-off, performance, aborted, friction, runway, wet, contaminated, snow, ice, risk, accident

18. Distribution Statement
Limited number of copies available from the Transportation Development Centre

19. Security Classification (of this publication) Unclassified	20. Security Classification (of this page) Unclassified	21. Declassification (date)	22. No. of Pages 537	23. Price

TDC/CDT 79-005
Rev 88

Canada

Transports Canada Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada
TP 10888E

2. N° de l'étude
7142

3. N° de catalogue du destinataire

4. Titre et sous-titre
AIRCRAFT TAKE-OFF PERFORMANCE AND RISKS FOR WET
AND CONTAMINATED RUNWAYS IN CANADA

5. Date de la publication
Juillet 1991

6. N° du document de l'organisme exécutant
88279

7. Auteur(s) David C. Biggs, Gordon B. Hamilton, Ken D.J. Owen
Walter McLeish, L.D. Reid

8. N° de dossier — Transports Canada
D1455-203-2

9. Nom et adresse de l'organisme exécutant
SYPHER:MUELLER International Inc.
130 Slater Street, Suite 1025
Ottawa, Ontario K1P 6E2

10. N° de dossier — ASC
T8200-8-8522

11. N° de contrat — ASC ou Transports Canada

12. Nom et adresse de l'organisme parrain
Transportation Development Centre
200 Rene Levesque Blvd. West
Suite 601, West Tower
Montreal, Quebec H2Z 1X4

13. Genre de publication et période visée
Rapport final

14. Agent de projet
Barry Myers

15. Remarques additionnelles (Programmes de financement, titres de publications connexes, etc.)

16. Résumé

Le présent rapport fait état des résultats d'une étude sur les risques reliés aux performances dégradées lors des décollages interrompus et ininterrompus des pistes mouillées et contaminées. Une révision exhaustive des données sur les accidents et incidents à l'échelle mondiale fut effectuée en vue de déterminer la gravité du problème et d'identifier les facteurs en cause. Les caractéristiques de l'état des pistes, la corrélation des dispositifs de mesure de frottement des pistes avec le frottement que connaissent les aéronefs, et l'estimation des performances au décollage des pistes mouillées et contaminées ont été révisés. On a examiné des estimés des performances à partir du rapport qui existe entre le frottement sur une piste contaminée et le frottement sur une piste sèche. On trace également les grandes lignes d'une méthode permettant de classifier l'état des pistes, méthode qui est basée sur les SARPS de l'OACI, les essais FAA/NASA et les pratiques des pays et des lignes aériennes de premier plan. On a établi la fréquence des pistes mouillées et contaminées au Canada, la probabilité d'un événement critique lors du roulement au décollage et la distribution de la masse au décollage. Ces distributions de fréquences et de probabilités, et les données sur les pistes, la température et les performances des aéronefs ont été utilisées dans le cadre d'une analyse probabiliste de la possibilité des accidents au décollage. Plusieurs contre-mesures ont été examinées, dont le moyen JAR de conformité acceptable pour des pistes mouillées et contaminées. Finalement, des recommandations sont formulées relativement aux autres activités nécessaires pour pouvoir tenir compte de façon efficace des pistes mouillées et contaminées dans les règlements régissant les performances au décollage.

17. Mots clés

18. Diffusion
Le Centre de développement des transports dispose d'un nombre limité d'exemplaires

19. Classification de sécurité (de cette publication)
Non classifiée

20. Classification de sécurité (de cette page)
Non classifiée

21. Déclassification (date)

22. Nombre de pages

23. Prix

CDT/TDC 79-005
Rev 88

Canada

AEROPLANE TAKE-OFF PERFORMANCE AND RISKS FOR WET AND CONTAMINATED RUNWAYS IN CANADA

SUMMARY

1. INTRODUCTION

The Transportation Safety Board of Canada recommended that research be undertaken into the risks associated with degraded performance during rejected and continued take-off from wet and contaminated runways. Current Canadian and USA regulations for calculating take-off performance are applicable to dry runway surfaces only, although FAA advisory information is available. Regulatory and advisory approaches vary widely among the major aviation countries, and no consensus has yet been achieved on methods to deal with degraded performance on take-off. Of the two civil airworthiness requirements which govern the design standards for most large transport category aeroplanes, USA FAR 25 and the European JAR 25, only JAR 25 speaks to the subject of contaminated runway performance.

The study was divided into three phases and this report gives the results of the first phase. The objectives of this phase of the study were:

- to determine the risks of take-off from wet and contaminated runways in Canada,
- to identify/develop methods and procedures for including wet and contaminated runway effects on take-off performance calculations, and
- to identify counter measures for reducing the risk.

2. REVIEW OF ACCIDENTS AND INCIDENTS

The study undertook a comprehensive review of world-wide accident and incident data to identify the severity of the problem and the factors involved. Eighty four take-off accidents involving jet aircraft of first world countries since 1970 were identified. Of these accidents, 83% were aborted take-off accidents, and 20% were on wet or water covered runways and 13% on snow, slush or ice covered runways. Of the aborted take-off accidents, the runway was wet or contaminated in only 6% of accidents where the aircraft stopped on the runway, but was wet or contaminated in 43% of accidents where the aircraft left the runway. In the abort-run-off-runway accidents, the decision to abort the take-off due to a critical event which occurred after the V_1 speed is much more common on dry runways than on wet runways. A late decision to abort is also common on snow and slush covered runways due to a common critical event being slow acceleration.

Fatalities occurred in 11% of the take-off accidents, the most severe being accidents where the aeroplane continued take-off and crashed. The occurrence of fire usually increases the severity of the accident and fire is common in aborted take-off accidents on dry runways, but is relatively uncommon when the runway is wet or contaminated..

There have been 3 take-off accidents involving jet aircraft in Canada since 1970 and, similar to the world trend, the runway was wet or contaminated in one of these accidents. Since 1986 engine failures have occurred once in every 76,000 take-offs of jet aircraft in Canada and some other type of critical event has occurred once in every 40,000 take-offs. About 12 jet aircraft take-offs in Canada are aborted per year, half of these due to engine failure. On average, 6 take-offs in Canada are continued after some critical event; tire failure comprises 40% of these critical events and engine failure only 12%.

3. RUNWAY FRICTION CHARACTERISTICS AND MEASUREMENT

A review of runway condition characteristics using the dry runway as a baseline was undertaken to understand the current theories of the relationship of surface texture to water, slush, snow, and ice contamination and to viscous and dynamic hydroplaning.

The correlation of runway friction test devices between themselves and with the friction experienced by aeroplanes in controlled and day to day conditions was explored. The review indicates that influences of variables such as tire type, size and tread pattern, speed, water depth, surface type and texture, etc. can be critical when correlating the different friction measures.

The concept of monitoring friction using ground vehicle measurements and correlating the values from the various ground vehicles as identified by ICAO Fig. 5.1 Doc. 9137 for snow and ice conditions has been supported by the majority of investigators at least in concept if not in terms of measurement data. The agreement between the magnitude of ground test friction measurements and aeroplane effective friction is generally poor, but the ratios of dry to wet friction are similar between ground vehicles and the aeroplane. Recent NASA test data includes methods for predicting the aeroplane effective braking friction from the ground tests to an accuracy of plus or minus 0.1μ for a range of test conditions for several types of aeroplanes.

Measures to improve runway friction were also reviewed. USA tests indicate that runway grinding and grooving can double the effective braking ratio, μ_{wet}/μ_{dry} on wet and flooded runways. The ICAO recommended runway maintenance procedures were found to well summarize the procedures required to monitor runway friction and to prevent low friction due to runway contamination.

4. AEROPLANE TAKE-OFF PERFORMANCE

The impact of runway contamination on aircraft performance has been studied, analyzed and flight tested since the late 1950's. Take-off performance is affected on contaminated runways in three ways:

- decrease in braking effectiveness due to reduced braking friction between tires and runway;

- increased drag due to undercarriage displacement of the contaminant by the tires and the impingement of the contaminant on the aeroplane structure; and

- reduction in the directional control of the aircraft due to reduced friction between tires and runway.

Equations for calculating the displacement and impingement drag and the aquaplaning speed were obtained from a number of sources and slush drag coefficients for a number of aircraft types were also obtained.

The sidewards friction between the tire and the ground is reduced by any form of contamination, especially as the aeroplane approaches tire hydroplaning speed, and in the presence of a crosswind or engine failure this reduces the pilot's directional control of the aeroplane. Tests using the University of Toronto Institute of Aerospace Studies (UTIAS) B747 simulator indicated that at the minimum control ground speed (V_{mcg}) appropriate for a 35 knot crosswind on a dry runway, the pilot could not maintain directional control on a wet runway (μ=0.3) with a 25 knot cross wind. Similarly, the pilot could not maintain control on an icy runway (μ=0.1) at V_{cmg} speed in a 10 knot crosswind. The reduction in controllability has been allowed for in the operating procedures of some airlines by reducing the allowable crosswinds the aeroplane can take-off in on contaminated runways.

The performance data for A320, DC10, BA146, F-28, and B747-100 (B747 based on simulator data) clearly indicate that runway conditions significantly affect both the accelerate-stop (ASD) and take-off (TOD) distances. Comparison of the effects of particular types of contamination on the performance of different aircraft types is difficult because of the different methods used to describe and measure runway condition. Table 1 gives approximate values of the ratio of contaminated to dry values of the ASD and TOD for typical runway conditions.

Table 1. Ratio of Contaminated to Dry Values of ASD and TOD for Various Typical Runway Conditions

Runway Condition	Friction	Type	Ratio Contaminated / Dry B747[1]	A320[2]	F-28[3]	DC10[4]	BA146
Wet	good-med.	ASD	1.18	1.15	1.11		
		TOD	1.02	0.99			1.00
Water (6 mm 1/4")	good-med.	ASD	1.70	1.82	1.43		
		TOD	1.06	1.02			1.11
Slush (8 mm 1/3")	med.-poor	ASD	1.51	1.67	1.64	1.48	
		TOD	1.12	1.14			1.19
Compact Snow	med.-poor	ASD	1.43	1.46		1.28	
		TOD	1.05	0.92			1.00
Loose dry snow (20 mm 3/4")	med.-poor	ASD	1.46	1.65	1.50	1.32	
		TOD	1.13	1.15			1.10
Ice	poor	ASD	2.07		3.35	1.76	
		TOD	1.04	0.92			1.00

Notes:

1. Aircraft-runway $\mu = 0.1$ for ice, 0.2 for slush, loose and compact snow, and 0.3 for water and wet conditions for B747.
2. Friction values for A320 implicit when type of contamination is given.
3. Braking coefficient for F-28 assumed to be: good 0.5, good-medium 0.4, medium-poor 0.3 and poor 0.2.
4. Distance corrections for DC10 without reverse thrust.

The ratios for each type of contaminant are fairly similar for the different aircraft types, especially for the B747 and A320. Differences between the ratios could be due as much to differences in classifying runway conditions when deriving the data, as actual differences in aircraft performance, especially for the DC10 and F-28. The effect of slush, snow and water on TOD is fairly similar between aircraft types, but the effect of wet, compact snow and ice conditions varies greatly.

5. RISK ANALYSIS

The margin of safety on take-off can be thought of as the difference between the runway length available and the runway length required for an aborted or continued take-off, given a critical event at V_1. On a dry runway the margin of safety, by regulation, must be positive.

Aircraft usually take-off with some margin of safety on dry runways because:

- for many departures the runway length available is greater than that required at maximum take-off weight for that aircraft, and
- aircraft typically have take-off weights 5% to 20% less than the allowed maximum take-off weight for the aircraft from the runway it is taking-off from, and this reduces the required take-off distance by 10% to 35%.

However, if the runway is wet or contaminated the extra distance required for an accelerate-stop or take-off may result in a negative margin of safety; that is that the ASD or TOD would exceed the available runway length.

The distribution of runway conditions were determined for the Halifax, Ottawa, Toronto (Pearson), Calgary, Prince George and Edmonton (Municipal) airports. Based on these airports, runways in Canada during the coldest 5 months are wet or contaminated, on average, about a third of the time, but this can vary from 10-65% of the time depending on the airport and month. During December to February the percentage of the time the runways are contaminated are as follows:

10-30%	snow covered
2-20%	ice covered
2-3%	slush covered
1-3%	frost covered

Typical depths of contaminants at these airports are 0.6 in. of loose snow, 1.5 in. of drifting snow and 0.3 in. of slush. Runway friction measured using ground vehicles varies significantly for any one contaminant, but average values are 0.8 for bare and dry, 0.7 for bare and wet, 0.4 for snow, slush or frost and 0.35 for ice patches. During the warmer seven months runways are wet between 5 and 15% of the time at most airports.

A probabilistic model was developed for estimating the margin of safety and the risk of a take-off accident for a particular aircraft type at a given airport allowing for variation in:

- wind direction and speed,
- temperature,
- choice of runway,
- runway condition,
- take-off weight,
- type and time of critical event on take-off,
- pilot response time, and
- whether reverse thrust was used.

Data for the model were compiled for the B747-100, A320 and BA146 aeroplanes and for the above four airports and Pearson International Airport in Toronto.

The margin of safety on take-off was found to be less than zero in roughly 1 out of every 1000 jet departures in Canada due to the non-accountability of runway conditions in the performance calculations. The take-off accident risks for B747 and A320 departures vary from 0.1×10^{-6} for departures from Toronto to 1.5×10^{-6} for departures from Halifax. Accident risks for the BA146 are less than 10^{-9} at Toronto, Calgary, Ottawa and Halifax, and are between 10^{-8} and 10^{-7} for Prince George and Edmonton Municipal airports. At Pearson International Airport in Toronto when a B747 aircraft lines up for take-off on a snow covered runway the probability of an overshoot accident is 1×10^{-6} and on an ice covered runway the probability of a serious accident is one in 500,000; much greater than acceptable risks due to other types of aviation accidents.

Use of reverse thrust in crosswind conditions which would likely not affect the controllability of the aircraft reduces the overall take-off accident risk (i.e. overall crosswind conditions) by 25% and reduces the risk of a serious accident by about a third.

6. CLASSIFICATION SYSTEM FOR RUNWAY CONDITIONS

The classification systems for runway conditions used by ICAO Standards and Recommended Practises (SARPS), FAA/NASA B727/B737 trials, the practices of leading countries, the military, and leading airlines were reviewed. Some countries have guidance material for the use of runway condition reports in take-off performance accountability under certain provisos, but actual regulatory standards based upon internationally agreed friction measuring devices and practices do not yet exist. Also the runway condition braking codes are dissimilar between airlines and between countries.

The acceptability of the Annex 15 ICAO SNOWTAM Section H (runway friction measurement or braking action) for describing runway conditions has been challenged by the JAR/Airbus Industrie decision not to accept anything other than a description of the contaminant and its depth for the accountability of aeroplane take-off performance. However, no differences have been filed by member countries against ICAO Annex 14 and Annex 15 SARPS.

Until ICAO is successful in increasing the scope of standards for contaminated runway flight operations requiring friction measurements which translate into reliable aeroplane braking effectiveness values, the best that can be achieved for civil flight operations is agreement on a code of runway conditions. This code could be used for adjusting take-off performance based on the aeroplane flight manual for dry/contaminated friction ratios. A sample of possible code was developed and is given in Table 2.

Table 2. Sample Stop Distance Code for MU-meter

Description of Runway Condition	Code for Stop Dist (SD) from JAR/AIRBUS	Code Calculated From Mu-Meter Typical Measurements			Verbal Description Braking
		μMUM	μeff	MUM Code	
Dry	μdry	Over 0.75	0.50 (Ref. 56 Table A2 & A3)		Good
Wet (under 3mm)	$\frac{\mu dry}{2}$	0.55 to 0.75	0.155 to 0.3 (Ref. 56 Table VI 150 psi)	$\frac{\mu dry}{1.7 \text{ to } 3.2}$	Good to Medium
Contaminated (Water, snow and ice*)	$\frac{\mu dry}{4}$	0.17 to 0.47 (ICAO Fig. 5.1 Doc 9137)	0.055 to 0.25 (Ref. 56 Equation 5)	$\frac{\mu dry}{2 \text{ to } 9.1}$	Medium to Poor

* ICE = if glare ice it would likely be unreliable to measure friction and not suitable for take-off

μMUM = μ value measured by Mμ-Meter

The calibration of runways under various dry, wet and contaminated conditions and a range of temperatures would provide a statistical calibration record suitable for assisting in the search for universality of recording and collating reliable runway friction data. The statistical calibration of the runway could also be used for adjusting the measured ground vehicle friction.

7. COUNTER MEASURES

Counter measures are intended to be effective under any combination of tire, runway surface and runway contamination conditions. Accordingly, counter measures should be considered as a means to predict performance under known conditions, or as a means to monitor performance during take-off so that appropriate action may be taken by the pilot. Aeroplane deceleration systems were also considered as counter measures.

The JAR acceptable means of compliance for wet and contaminated runways is used in Japan and some European countries, including Norway and Sweden where the weather conditions are similar to Canada. Under the JAR approach, runway condition is included in the performance calculations and the V_1 speed may be reduced thereby reducing the exposure of engine failure leading to V_1 and increasing the runway available to stop. A reduced V_1 speed increases the take-off distance as the aircraft must be capable of a continued take-off after engine failure from a lower speed. However, the TOD is determined to a screen height of only 15 feet rather than 35 feet thereby reducing the potential impact of this requirement on take-off weights. The minimum V_1 speed chosen must still meet the requirement of not being below V_{mcg} for the given condition.

A number of performance monitoring systems have been developed which vary in complexity from checking the airspeed at a predetermined point along the runway, to NASA's TOPMS system which continually monitors the aircraft's speed in relation to the calculated position of achieving the V_1 and V_R speeds and graphically displays the results. No take-off monitoring system is currently in civil use today and tests by 30 USA airline pilots of the TOPMS system indicate that there are still some questions to be resolved before the system could be considered for operational use.

Contamination reduces the friction between the aircraft tires and the runway, thus increasing the distance required to bring the aircraft to a stop. Braking mechanisms which do not rely on tire-runway friction would not be affected by any runway contamination. Engine reverse thrust and emergency brake parachutes are therefore effective forms of braking on contaminated runways. Reverse thrust is often used in aborted take-offs, but if an engine failure has occurred, the braking force provided by reverse thrust is asymmetric and this reduces the controllability of the aircraft. The severity of an overshoot accident can be reduced by the use of arrestors for decreasing the aeroplane speed in the overrun area or a flat outrun area at the end of the runway.

8. CONCLUSIONS

The report concludes that the accelerate-stop distance is increased by approximately 15% on wet runways, 50% on snow, 75% on water deeper than 3 mm and 100% on ice covered runways; and that typical depths of 15 mm (0.6 in.) loose snow and 8 mm (0.3 in.) slush increase take-off distance by 10%.

Current regulations allow for a 15% safety margin in the TOD for take-offs on dry runways, but this margin is not sufficient to account for the greater take-off distance (with no engine failure) on runways with more than 13 mm (½ in.) of slush or 25 mm (1 in.) of loose dry snow for some aircraft types.

Wet and contaminated runways are rarely the only cause of take-off accidents but they reduce the margin of safety available so that accidents are more likely under such conditions.

The combination of contaminated runway and a critical event such as engine failure near V_1 pose threats to safety under current regulations.

The accident risks in Canada of take-offs from wet or contaminated runways is approximately twice the risk of take-offs from dry runways and the accident risk from contaminated runways is greater than other acceptable aircraft accident/incident risks.

There is strong evidence that accurate and reliable values of aeroplane effective braking friction can be estimated for a given type of aeroplane and a given runway from friction values for a specific ground test vehicle.

The search for universality of friction correlation is close to success and requires agreement on day to day procedures by airports, airlines, authorities and aeroplane manufacturers.

9. RECOMMENDATIONS

It is recommended that the following tasks be undertaken in Phase II of the study:

(a) Obtain, or estimate, contaminated runway performance for the Boeing 737 and 727 and estimate the accident risks for those aircraft. Examine runway condition data at more airports, including small remote airports. From these and the accident risks determined in Phase I, estimate the accident risks for the whole of Canada.

(b) Determine the risk reduction, in terms of reduced fatalities, hull damage and airport disruption, of selected counter measures, including regulatory changes similar to those in JAR 25X1591.

(c) Determine the operational problems associated with, and impact of, the selected counter measures, particularly introduction of JAR 25X1591, and the experiences of other countries using the counter measure.

(d) Estimate costs of selected counter measures, including introduction of JAR 25X1591; these include take-off weight reduction, increased aircraft capital and maintenance expenditure, crew training costs, expenditure on runway maintenance and improvements, etc.

(e) Determine the relative benefit-cost relationship for the selected counter measures, and draw conclusions on those that seem the most promising from a benefit-cost perspective.

(f) Research Canada's method of establishing runway condition, including the use of ground vehicles for measuring friction, and determine if the quality and completeness of data is adequate for use with the JAR 25X1591 requirements.

(g) Undertake a pilot project to calibrate selected runways at large and small airports in Canada over a period of one year and to estimate aeroplane effective braking data as a means to prepare for the adoption of take-off accountability.

Other recommendations are:

(h) Canada should evaluate its current runway ground vehicle friction measurement procedures and runway condition reporting to comply fully with ICAO Annex 14 and Annex 15.

(i) Canada should offer to undertake with other ICAO States a cooperative project designed to achieve international agreement on the criteria needed for universality of runway friction data measurement and estimation of aeroplane effective friction codes which could lead to amendments to ICAO SARPS for take-off performance accountability.

LES PERFORMANCES DES AÉRONEFS ET LES RISQUES RELIÉS AU DÉCOLLAGE DES PISTES MOUILLÉES ET CONTAMINÉES AU CANADA

RÉSUMÉ

1. INTRODUCTION

Le Bureau de la sécurité des transports du Canada a recommandé qu'on mène des recherches sur les risques reliés aux performances dégradées lors du décollage interrompu ou ininterrompu des pistes mouillées et contaminées. Les règlements canadiens et américains actuels relativement au calcul des performances au décollage s'appliquent aux pistes sèches seulement, bien que la Federal Aviation Authority (FAA) dispose d'informations à titre consultatif. Les façons d'aborder la question sur le plan réglementaire et administratif varient beaucoup chez les majeurs pays d'aviation et on n'est toujours pas arrivé à un consensus quant aux méthodes permettant de se pencher sur les performances dégradées au décollage. Des deux exigences civiles en matière de navigabilité régissant les normes de design pour la majorité des gros aéronefs de transport, à savoir la Federal Airworthiness Requirement 25 (FAR) américaine et la Joint Airworthiness Requirement 25 (JAR) européenne, seule la JAR 25 aborde les performances sur les pistes contaminées.

L'étude a été divisée en trois parties et le présent rapport donne les résultats de la première partie. Cette partie de l'étude avait pour but :

- de déterminer les risques associés au décollage des pistes mouillées et contaminées au Canada,
- d'identifier et d'élaborer des méthodes et procédures permettant de tenir compte des effets des pistes mouillées et contaminées sur les calculs des performances au décollage, et
- d'identifier des contre-mesures visant à réduire les risques.

2. RÉVISION DES ACCIDENTS ET DES INCIDENTS

L'étude consistait en une révision exhaustive des données sur les accidents et incidents à l'échelle mondiale, en vue de déterminer la gravité du problème et d'identifier les facteurs en cause. On a identifié quatre-vingt-quatre accidents au décollage impliquant des aéronefs à réaction des pays du monde industrialisé, qui sont survenus depuis 1970. Quatre-vingt-trois p. 100 de ces accidents étaient des accidents au décollage interrompu, et 20 p. 100 d'entre eux sont survenus sur des pistes mouillées ou couvertes d'eau et 13 p. 100 se sont produits sur des pistes couvertes de neige, de neige fondante ou de glace. Pour ce qui est des accidents au décollage interrompu, la piste fut mouillée ou couverte de dépôts dans seulement 6 p. 100 des accidents dans lesquels l'aéronef s'est immobilisé sur la piste, mais fut mouillée ou contaminée dans 43 p. 100 des accidents dans lesquels l'aéronef a quitté la piste. Quant aux accidents au décollage interrompu dans lesquels l'aéronef a quitté la piste, la décision d'interrompre le décollage en raison d'un événement critique survenu après que la vitesse V_1 a été atteinte, revient beaucoup plus souvent sur les pistes sèches que sur les pistes mouillées. Une décision tardive d'interrompre le décollage en raison d'un événement critique courant, à savoir une accélération lente, revient également souvent sur les pistes couvertes de neige ou de neige fondante.

Les accidents au décollage, dont les plus graves impliquaient un aéronef qui a poursuivi les manoeuvres du décollage pour ensuite s'écraser au sol, ont fait des victimes dans 11 p. 100 des cas. Les incendies augmentent en général la gravité de l'accident et ils se produisent souvent dans des accidents au décollage interrompu d'une piste sèche, mais peu souvent lorsque la piste est mouillée ou contaminée.

On dénombre trois accidents au décollage impliquant des aéronefs à réaction qui ont eu lieu au Canada depuis 1970 et, tout comme la tendance à l'échelle mondiale, la piste fut mouillée ou contaminée dans un des trois accidents. Depuis 1986, les ruptures réacteur ont eu lieu dans un décollage sur 76 000 des aéronefs à réaction au Canada et un autre événement critique quelconque s'est produit dans un décollage sur 40 000. Environ 12 décollages effectués par les aéronefs à réaction au Canada sont interrompus annuellement, dont la moitié sont attribuables à une rupture réacteur. En moyenne, 6 décollages au Canada ne sont pas interrompus après un événement critique ; la rupture des pneus représente 40 p. 100 des événements critiques, tandis que la rupture réacteur n'en représente que 12 p. 100.

3. LES CARACTÉRISTIQUES DE FROTTEMENT DE LA SURFACE DES PISTES ET LA FAÇON DE LES MESURER

On a effectué une révision de l'état des pistes en se servant de la piste sèche comme base en vue de comprendre les théories actuelles sur le rapport qui existe entre la texture superficielle et la contamination par eau, neige fondante, neige et glace d'une part et entre la texture superficielle et l'aquaplanage visqueux et dynamique d'autre part.

On a également examiné la corrélation entre les dispositifs de mesure du frottement de la surface des pistes et entre ces dispositifs et le frottement des aéronefs dans des conditions contrôlées et courantes. Cette révision révèle que les variables, telles que le genre et la largeur du pneu, la bande de roulement, la vitesse, la profondeur de la nappe d'eau et le genre et la texture de la surface, etc., peuvent être des facteurs critiques lorsqu'on établit une corrélation entre les différentes mesures de frottement.

La majorité des enquêteurs souscrivent, du moins en théorie sinon en termes de mesures, au concept qui consiste à surveiller le frottement en ayant recours aux mesures effectuées par les véhicules au sol et à corréler les mesures obtenues par les différents véhicules au sol, tel que l'indique la figure 5.1 dans le document 9137 de l'OACI pour des chaussées couvertes de neige et de glace. En général, il existe une faible corrélation entre les mesures de frottement au sol et le frottement efficace de l'aéronef, mais les rapports entre le frottement sur les pistes sèches et le frottement sur les pistes mouillées sont semblables pour les véhicules au sol et l'aéronef. De récentes données d'essai de la NASA renferment des méthodes pour prédire le frottement efficace du freinage de l'aéronef à partir de mesures au sol, qui ont un niveau de précision de plus ou moins 0,1 μ pour une gamme de conditions d'essai pour plusieurs types d'aéronefs.

On a de plus révisé les méthodes visant à améliorer le frottement de la surface des pistes. Des essais menés aux États-Unis révèlent que les pistes brossées ou striées peuvent doubler le rapport de freinage efficace, μmouillée/μsèche sur des pistes mouillées et inondées. On a trouvé que les procédures pour entretenir les pistes qu'a recommandées l'OACI résument bien les procédures nécessaires à la surveillance du frottement de la surface des pistes et à la prévention d'un faible frottement due à la contamination des pistes.

4. LES PERFORMANCES DES AÉRONEFS AU DÉCOLLAGE

Depuis la fin des années 1950, on a étudié, analysé et essayé en vol l'impact qu'a la contamination des pistes sur les performances des aéronefs. Les pistes couvertes de dépôts peuvent nuire aux performances des aéronefs au décollage de trois façons :

- réduire l'efficacité des freins en raison d'un plus faible frottement entre les pneus et la piste ;
- augmenter la traînée en raison des pneus qui projettent le dépôt sur le train d'atterrissage et du choc des projections sur la structure de l'aéronef ; et
- réduire le contrôle directionnel de l'aéronef en raison du frottement moins important entre les pneus et la piste.

Les équations pour calculer la traînée due au déplacement du fluide, la traînée due au choc des projections et la vitesse d'aquaplanage ont été tirées de plusieurs sources. Par ailleurs, on a obtenu les coefficients de traînée due à la neige fondante pour plusieurs types d'aéronefs.

Le frottement latéral entre le pneu et le sol est réduit par toute forme de dépôt, surtout à mesure que l'aéronef atteint la vitesse à laquelle les pneus font de l'aquaplanage. En présence de vents traversiers ou de rupture réacteur, la réduction du frottement latéral réduit le contrôle directionnel qu'a le pilote sur l'aéronef. Les essais utilisant le simulateur B747 de l'University of Toronto Institute of Aeropsace Studies (UTIAS) ont indiqué qu'à la vitesse minimale de contrôle au sol (V_{mcg}) appropriée en présence de vents traversiers de 35 noeuds sur une piste sèche, le pilote ne pouvait pas garder le contrôle directionnel sur une piste mouillée ($\mu = 0,3$) en présence de vents traversiers de 25 noeuds. De même, le pilote ne pouvait pas garder le contrôle sur une piste couverte de glace ($\mu = 0,1$) à la vitesse V_{mcg} en présence de vents traversiers de 10 noeuds. Il s'agit d'une réduction de contrôle dont a tenu compte dans les procédures de fonctionnement de certaines lignes aériennes, en réduisant la vitesse admissible des vents traversiers dans lesquels l'aéronef peut décoller d'une piste contaminée.

Les données sur les performances du A320, DC10, BA146, F-28 et B747-100 (le B747 est basé sur des données obtenues par simulateur) indiquent clairement que l'état des pistes touche de façon importante les distances accélération-arrêt (DAA) et de décollage (DD). En raison des différentes méthodes utilisées pour décrire et mesurer l'état des pistes, il est difficile de comparer les effets qu'ont les types de dépôts en particulier sur les performances des différents aéronefs. Le tableau 1 donne des valeurs approximatives du rapport qui existe entre les valeurs obtenues sur des pistes contaminées et sèches pour la DAA et la DD selon l'état des pistes type.

Tableau 1. Rapport entre les valeurs obtenues sur les pistes contaminées et sèches pour la DAA et la DD, selon l'état de la piste.

État de la piste	Frottement	Type	Rapport piste contaminée/sèche				
			B747[1]	A320[2]	F-28[3]	DC10[4]	BA146
Mouillé	bon-moyen	DAA	1,18	1,15	1,11		
		DD	1,02	0,99			1,00
Eau (6 mm 1/4 po)	bon-moyen	DAA	1,70	1,82	1,43		
		DD	1,06	1,02			1,11
Neige fondante (8 mm 1/3 po)	moyen-faible	DAA	1,51	1,67	1,64	1,48	
		DD	1,12	1,14			1,19
Neige compacte	moyen-faible	DAA	1,43	1,46		1,28	
		DD	1,05	0,92			1,00
Neige sèche fraîchement tombée (20 mm 3/4 po)	moyen-faible	DAA	1,46	1,65	1,50	1,32	
		DD	1,13	1,15			1,10
Glace	faible	DAA	2,07		3,35	1,76	
		DD	1,04	0,92			1,00

Notes :

1. Aéronef-piste μ = 0,1 pour glace, 0,2 pour neige fondante, neige fraîchement tombée et neige compacte, et 0,3 pour eau et les chaussées mouillées pour un B747.
2. Les valeurs de frottement pour l'A320 sont implicites lorsqu'on indique le type de dépôt.
3. On suppose que le coefficient de freinage pour le F-28 est bon à 0,5, bon-moyen à 0,4, moyen-faible à 0,3 et faible à 0,2.
4. Corrections de distance pour un DC10 sans inverseurs de poussée.

Les rapports pour chaque type de dépôt varient peu d'un type d'aéronef à un autre, surtout pour le B747 et l'A320. Les différences entre les rapports pourraient être autant attribuables aux différences dans le classification de l'état des pistes lorsqu'on obtient des données, qu'aux différences réelles entre les performances des aéronefs, surtout pour le DC10 et le F-28. La neige fondante, la neige et l'eau ont à peu près le même effet sur la DD chez les différents types d'aéronefs, mais l'effet qu'ont les chaussées mouillées, la neige compacte et la glace varie beaucoup.

5. ANALYSE DES RISQUES

La marge de sécurité au décollage est essentiellement la différence qui existe entre la longueur de la piste disponible et la longueur de la piste nécessaire à un décollage interrompu ou ininterrompu, étant donné un événement critique à V_1. Les règlements stipulent que la marge de sécurité doit être positive sur une piste sèche.

En général, les aéronefs décollent des pistes sèches en dispensant d'une certaine marge de sécurité :

- pour plusieurs décollages, la longueur de la piste disponible est supérieure à la longueur exigée pour la masse maximale au décollage pour l'aéronef en question ;
- les aéronefs ont, en général, une masse au décollage qui est inférieure de 5 à 20 % à la masse maximale admissible au décollage pour la piste en question, ce qui réduit de 10 à 35 % la distance requise au décollage.

Toutefois, si la piste est mouillée ou contaminée, la distance supplémentaire requise pour une accélération-arrêt ou un décollage peut occasionner une marge de sécurité négative ; c'est-à-dire, la DAA ou la DD surpasserait la longueur de la piste disponible.

La distribution de l'état des pistes a été déterminée pour les aéroports à Halifax, Ottawa, Toronto (Pearson), Calgary, Prince George et Edmonton (municipal). Selon les données sur ces aéroports, les pistes au Canada sont en moyenne mouillées ou couvertes de dépôts le tiers du temps durant les 5 mois les plus froids, mais cela peut varier de 10 à 65 % du temps, selon l'aéroport et le mois. On indique ci-dessous le pourcentage du temps que les pistes sont couvertes de dépôts entre les mois de décembre et février :

10 à 30 %	couverte de neige
2 à 20 %	couverte de glace
2 à 3 %	couverte de neige fondante
1 à 3 %	couverte de gelée blanche

La profondeur des dépôts à ces aéroports est en général 0,6 po de neige fraichement tombée, 1,5 po de poudrerie basse et 0,3 po de neige fondante. Le frottement sur la piste mesurée à l'aide de véhicules au sol varie grandement pour un dépôt, mais les valeurs moyennes sont les suivantes : 0,8 pour des pistes propres et sèches, 0,7 pour des pistes propres et mouillées, 0,4 pour les pistes couvertes de neige, de neige fondante ou de gelée blanche et 0,35 pour les pistes ayant des plaques de glace. Les pistes dans la plupart des aéroports sont mouillées entre 5 et 15 % du temps durant les sept autres mois plus chauds.

On a mis au point un modèle probabiliste en vue d'estimer la marge de sécurité et la possibilité qu'un accident au décollage survienne pour un type précis d'aéronef à un aéroport donné, en tenant compte des variations dans :

- la direction et la vélocité des vents,
- la température,
- la piste choisie,
- l'état de la piste,
- la masse au décollage,
- le genre d'événement critique au décollage et le moment où il survient,
- le temps de réaction du pilote, et
- l'inversement ou non de la poussée.

On a compilé les données pour le modèle probabiliste pour les aéronefs B747-100, A320 et BA146 pour les quatre aéroports nommés ci-dessus et l'Aéroport international Lester B. Pearson-Toronto.

On a découvert que la marge de sécurité au décollage était inférieure à zéro dans environ 1 décollage sur 1000 effectués par les aéronefs à réaction au Canada en raison de l'état des pistes dont les calculs relativement aux performances des aéronefs n'ont pas tenu compte. Pour les aéronefs B747 et A320, la possibilité qu'un accident au décollage survienne, varie de 0,1 x 10^{-6} pour les décollages à Toronto à 1,5 x 10^{-6} pour les décollages à Halifax. Quant à l'aéronef BA146, la possibilité qu'un accident survienne est inférieure à 10^{-9} à Toronto, Calgary, Ottawa et Halifax et de 10^{-8} à 10^{-7} à l'aéroport de Prince George et à l'aéroport municipal d'Edmonton. À l'Aéroport international Lester B. Pearson-Toronto, lorsqu'un aéronef B747 fait la queue pour décoller d'une piste couverte de neige, la probabilité qu'un accident associé au dépassement de piste ait lieu est de 1 x 10^{-6} sur une piste couverte de glace et la probabilité qu'un accident grave survienne est 1 sur 500 000, soit une probabilité qui est beaucoup plus grande que les risques acceptables dûs aux autres types d'accidents d'aéronef.

L'inversement de la poussée en présence de vents traversiers qui n'affecteraient probablement pas le contrôle de l'aéronef, réduit de 25 % la possibilité en gros d'un accident au décollage (c.-à-d., les vents traversiers en général) et d'environ le tiers la possibilité qu'un accident grave se produise.

6. SYSTÈME DE CLASSIFICATION DE L'ÉTAT DES PISTES

On a passé en revue les systèmes de classification de l'état des pistes dont se servent les Normes et pratiques recommandées internationales de l'OACI (SARPS), les essais de la FAA/NASA avec le B727/B737, les pratiques dans les pays de premier plan, les armées, et les lignes aériennes de premier plan. Certains pays disposent de documents à titre d'information portant sur l'utilisation des rapports de l'état des pistes lorsqu'on tient compte des performances au décollage sous réserve de certaines conditions, mais les normes réglementaires réelles qui reposent sur les dispositifs de mesure de frottement et les pratiques à l'échelle internationale n'existent toujours pas. De plus, les codes de freinage selon l'état de la piste varient d'une ligne aérienne à une autre et d'un pays à un autre.

Le fait d'accepter la section H dans l'Annexe 15 du SNOWTAM de l'OACI (mesure du frottement de la surface des pistes ou de freinage) quant à la description de l'état des pistes a été contesté par la JAR/Airbus Industrie dans sa décision d'accepter uniquement la description du dépôt et de sa profondeur lorsqu'on tient compte des performances des aéronefs au décollage. Toutefois, aucun pays membre ne s'est opposé à l'Annexe 14 ou à l'Annexe 15 du SARPS de l'OACI.

Jusqu'à ce que l'OACI réussisse à élargir la portée des normes relativement aux opérations aériennes sur les pistes contaminées exigeant des mesures de frottement qui se traduisent en des valeurs fiables sur le freinage efficace des aéronefs, le mieux qu'on puisse faire sur le plan des opérations aérinnes civiles est de parvenir à une entente sur un code relativement à l'état des pistes. On pourrait se servir de ce code pour modifier les performances au décollage en fonction du manuel de vol de l'aéronef pour des rapports entre le frottement sur les pistes sèches/contaminées. On a élaboré un échantillon d'un code éventuel qui figure dans le tableau 2.

Tableau 2. Échantillon d'un code de distance d'arrêt pour un mumètre.

Description de l'état de la piste	Code pour Dist d'arrêt (DA) de JAR/AIRBUS	Code calculé à partir des mesures type effectuées par un mumètre			Description du freinage en langage clair
		μMUM	μeff	Code MUM	
Sèche	μsèche	plus de 0,75	0,50 (Réf. 56 Tableaux A2 & A3)		Bon
Mouillé (moins de 3 mm)	$\frac{\mu\text{sèche}}{2}$	0,55 à 0,75	0,155 à 0,3 (Réf. 56 Tableau VI 150 lb/po)	$\frac{\mu\text{sèche}}{1{,}7 \text{ à } 3{,}2}$	Bon à moyen
Contaminée (eau, neige, et glace*)	$\frac{\mu\text{sèche}}{4}$	0,17 à 0,47 (fig. 5.1 dans Doc. 9137 de l'OACI)	0,055 à 0,25 (Réf. 56 équation 5)	$\frac{\mu\text{sèche}}{2 \text{ à } 9{,}1}$	Moyen à faible

* GLACE = s'il y a de la glace réfléchissante, les mesures de frottement seront probablement douteuses et ne conviendraient pas au décollage.

μMUM = valeur μ mesurée par un mumètre.

La mesure des pistes ayant des chaussées sèches, mouillées ou couvertes de dépôts et dans une gamme de températures, donnerait un dossier de mesures statistiques qui pourrait contribuer à l'universalité de l'enregistrement et de la collecte de données fiables sur le frottement de la surface des pistes. Les mesures statistiques des pistes pourraient également servir à ajuster le frottement mesuré par les véhicules au sol.

7. CONTRE-MESURES

Les contre-mesures doivent être efficaces dans toute combinaison de pneu, de surface de la piste et de dépôt. Par conséquent, les contre-mesures devraient être considérées comme un moyen permettant de prédire les performances des aéronefs dans des conditions connues, ou comme moyen permettant de surveiller les performances au décollage pour que le pilote puisse prendre des mesures appropriées. On a également considéré les systèmes de freinage des aéronefs comme contre-mesures.

Le moyen JAR de conformité acceptable en matière de pistes mouillées et contaminées est utilisé au Japon et dans quelques pays européens, dont le Norvège et la Suède où la température est semblable à celle du Canada. En vertu de la méthode JAR, l'état de la piste est incorporé dans les calculs relativement aux performances et la vitesse V_1 peut être réduite, réduisant ainsi la probabilité d'une rupture réacteur à mesure que l'aéronef atteint la vitesse V_1 et augmentant la longueur de la piste disponible pour arrêter. Une vitesse V_1 moins rapide, augmente la distance au décollage, puisque l'aéronef doit être en mesure, après une rupture réacteur, d'effectuer un décollage ininterrompu à une vitesse moindre. Toutefois, la DD est établie à une hauteur-écran de seulement 15 pieds plutôt que de 35 pieds, réduisant ainsi la portée potentielle de cette exigence sur les masses au décollage. La vitesse minimale V_1 choisie doit quand même répondre à l'exigence voulant qu'elle ne soit pas inférieure à V_{mcg} pour la condition donnée.

Plusieurs systèmes de contrôle des performances ont été mis au point. Leur complexité varie, allant de la vérification de la vitesse par rapport à l'air à un endroit sur la piste déterminé à l'avance, jusqu'au système TOPMS de la NASA, qui surveille continuellement la vitesse de l'aéronef par rapport à l'endroit où les vitesses V_1 et V_R seront atteintes et qui présente les résultats sous forme de graphique. Aucun système de contrôle du décollage n'est utilisé actuellement sur le plan civil et les essais effectués par 30 pilotes américains avec le système TOPMS révèlent qu'il reste encore des problèmes à résoudre avant que le système puisse être utilisé.

Les dépôts réduisent le frottement entre les pneus de l'aéronef et la piste, augmentant ainsi la distance nécessaire pour immobiliser l'aéronef. Les mécanismes de freinage qui ne fonctionnent pas selon le principe de frottement entre les pneus et la piste, ne seraient pas touchés par les dépôts sur les pistes. Les inverseurs de poussée et les parachutes-freins de secours constituent donc des moyens efficaces de freinage sur des pistes couvertes de dépôts. La poussée est souvent inversée lors des décollages interrompus, mais s'il y a eu une rupture réacteur, la force de freinage découlant de l'inversion de la poussée est asymétrique, réduisant par conséquent le contrôle de l'aéronef. La gravité d'un accident associé au dépassement de piste peut être réduite en ayant recours aux dispositifs d'arrêt en vue de réduire la vitesse de l'aéronef dans la zone de dépassement ou dans l'aire de bout de piste.

8.CONCLUSIONS

Le rapport conclut que la distance accélération-arrêt augmente d'environ 15 % sur des pistes mouillées, de 50 % sur des pistes couvertes de neige, de 75 % sur des pistes couvertes d'une nappe d'eau dont la profondeur est supérieure à 3 mm et de 100 % sur les pistes couvertes de glace ; et que les profondeurs type de 15 mm

(0,6 po) de neige fraîchement tombée et de 8 mm (0,3 po) de neige fondante augmentent de 10 % la distance de décollage.

Les règlements actuels permettent une marge de sécurité de 15 % dans la DD pour les décollages des pistes sèches, mais cette marge ne suffit pas lorsqu'il faut tenir compte d'une distance de décollage plus longue (sans rupture réacteur) pour certains types d'aéronefs sur des pistes couvertes de plus de 13 mm (1/2 po) de neige fondante ou de 25 mm (1 po) de neige sèche fraîchement tombée.

Il est rare que les pistes mouillées et contaminées soient la seule cause des accidents au décollage, mais elles réduisent la marge de sécurité disponible de sorte que les accidents sont plus susceptibles de se produire sur de telles pistes.

Si un événement critique, tel qu'une rupture réacteur survenant près de la vitesse V_1, a lieu sur une piste contaminée, cela peut constituer un danger sur le plan de la sécurité en vertu des règlements actuels.

Au Canada, les risques qu'il y ait un accident lors du décollage d'une piste mouillée ou contaminée sont environ deux fois plus importants que les risques qu'il y ait un accident lors du décollage d'une piste sèche. Les risques qu'il y ait un accident sur une piste contaminée sont plus importants que les risques acceptables qu'il y ait d'autres accidents ou incidents d'aéronef.

Il est très évident que les valeurs précises et fiables du coefficient de freinage efficace des aéronefs peuvent être estimées pour un type donnée d'aéronef et pour une piste donnée à partir des valeurs de frottement obtenues par un véhicule d'essai au sol en particulier.

La recherche d'une corrélation de frottement universelle est presque terminée et demande que les aéroports, les lignes aériennes, les autorités et les fabricants d'aéronefs s'entendent sur les procédures courantes.

9. RECOMMANDATIONS

Il est recommandé que les tâches suivantes soient entreprises durant la partie II de l'étude :

(a) Obtenir ou estimer les performances des aéronefs Boeing 737 et 727 sur les pistes contaminées et estimer les risques d'accident pour ces aéronefs. Examiner les données sur l'état des pistes à plusieurs aéroports, y compris les petits aéroports éloignés. À partir de ces risques et des risques d'accident établis dans la partie I, estimer les risques d'accidents pour tout le Canada.

(b) Établir la mesure dans laquelle certaines contre-mesures, dont les changements sur le plan réglementaire semblables à ceux dans la JAR 25X1591, peuvent réduire les risques d'avoir des morts, de dommages au coque et de perturbation à l'aéroport.

(c) Déterminer les problèmes d'ordre opérationnel associés aux contre-mesures sélectionnées et l'impact de celles-ci, surtout l'introduction de la JAR 25X1591, et les expériences des autres pays qui ont recours à la contre-mesure.

(d) Estimer les coûts des contre-mesures sélectionnées, dont l'introduction de la JAR 25X1591 ; ces coûts comprennent la réduction de la masse au décollage, plus de dépenses en immobilisations et en entretien d'aéronefs, la formation des équipes, l'entretien et l'amélioration des pistes, etc.

(e) Déterminer le rapport coût-avantage relatif pour les contre-mesures sélectionnées, et tirer des conclusions sur celles qui semblent être les plus prometteuses du point de vue coût-avantage.

(f) Faire des recherches sur la méthode dont se sert le Canada pour déterminer l'état des pistes, dont le recours aux véhicules au sol pour mesurer le frottement, et déterminer si la qualité et l'état complet des données sont adéquats pour que ces données puissent être utilisés de concert avec les exigences de la JAR 25X1591.

(g) Entreprendre une étude pilote dans le but de mesurer les pistes sélectionnées aux grands et petits aéroports au Canada pendant un an et d'estimer les données sur le freinage efficace des aéronefs comme moyen permettant de tenir compte du décollage.

Autres recommandations :

(h) Le Canada devrait évaluer ses procédures actuelles en matière de mesure de frottement de la surface des pistes effectuées par les véhicules au sol et la communication de l'état des pistes pour qu'il observe complètement les Annexes 14 et 15 de l'OACI.

(i) Le Canada devrait entreprendre, avec d'autres États membres de l'OACI, un projet de coopération permettant de parvenir à une entente internationale sur les critères nécessaires à l'universalité de la mesure des données sur le frottement de la surface des pistes et sur l'estimation des codes de frottement efficace des aéronefs qui pourraient entraîner des modifications aux SARPS de l'OACI pour ce qui est de tenir compte des performances au décollage.

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1. INTRODUCTION

1.1 Problem

The Canadian Aviation Safety Board, which is now incorporated into the Transportation Safety Board of Canada, reviewed incidents of aeroplanes taking off on wet and contaminated runways and recommended that research be undertaken into the risks associated with degraded performance during rejected and continued take-off.

The variables which can effect the actual take-off performance are given below.

1.1.1 Aeroplane:

- tire pressure and wear, number of wheels and under carriage configuration.
- number of engines and where mounted.
- wing configuration
  - high, mid or low
  - take-off flaps
- thrust to weight ratio and C/G.
- geometry, take-off configuration, engine characteristics and their influence on under carriage drag, tire drag.
- the wing is free of ice and snow contamination.
- aircraft systems failure warning effectiveness.
- flight deck
  - crew coordination
  - crew responses to emergencies
  - compliance with AFM checks, ASI settings for V_1, V_R, V_{LO}, and V_2 appropriate to airfield elevation and weather conditions.

1.1.2 Runway Surface:

- black top
- concrete
- plain or grooved
- crowned for water run-off
- gradient - constant, rolling
- rubber contamination

1.1.3 Types of Runway Contamination:

- damp
- standing water (pooling)
- downpour (microburst)
- slush - natural and with or without sand
  - due to treatment of snow and ice with urea products
- snow - wet or dry and with or without sand
- ice - wet or dry and with or without sand

Although airworthiness authorities have recognized and accepted rational and factored performance methods for landing under wet runway conditions, they have not done so for AFM take-off performance.

Current Canadian and USA regulations for calculating take-off performance are applicable to dry runway surfaces only, although FAA advisory information is available. Regulatory and advisory approaches vary widely among the major aviation countries, and no consensus has yet been achieved on methods to deal with degraded performance on take-off.

1.2 International Practice

1.2.1 ICAO

ICAO issues guidelines for setting aeroplane performance requirements, but in neither Annex 6, Operations of Aircraft, nor Annex 8, Airworthiness of Aircraft, of these guidelines is there any specific reference to the need for member states to provide for aeroplane take-off or landing information on contaminated runways.

The International Civil Aviation Organization (ICAO) Airport Services Manual (Doc 9137 - AN/898), Part 2, Pavement Surface Conditions, 1984 Edition a copy of which is provided in Appendix A, discusses "the general concern over the adequacy of the available friction between aeroplane tires and the runway surface under certain operating conditions, such as when there is snow, slush, ice or water".

Also, the ICAO Airworthiness Technical Manual, Part III, Section 8, Operating Limitations and Information a copy of which is provided in Appendix B, describes the characteristics of the effect of slush or water-covered runways on take-off performance due to retardation effects on wheels running through the slush, and the drag due to impingement on the aeroplane of spray thrown up by the wheels. Since the material is contained within the Technical Manual, it is only intended to guide contracting states in the development of their national codes. The material has no mandatory status and states are not required to notify any differences that may exist between their standards and the practices published in the manual. The manual does state that operation from slush covered runways is one of a number of problems that, although it existed with piston engine aeroplanes, is more acute with turbine powered aeroplanes.

ICAO Annex 15, Aeronautical Information Services, July 87 Edition provides for a SNOTAM to be issued to pilots describing runway conditions and braking action as an international Standard and Recommended Practice (SARP). A copy of the Annex 15 Appendix 2 SNOWTAM is provided in Annex 1 to Section 6.

Although the SNOWTAM includes a section on braking action, ICAO realizes, as do most States, that the variety of methods in use to measure and report runway friction mean that no one method has been singled out as the most effective or efficient. The essential ingredients are apparent and the airport authority should be responsible for the various measurements for reporting pavement condition to the dissemination agency. However, in States where the airports are non-state owned and operated, almost insurmountable difficulties arise in standardizing the measuring and reporting of runway friction data in a timely and consistent manner unless the national aviation authority mandates the requirement. Such data is essential for pilots to estimate take-off performance if the Aeroplane Flight Manual (AFM) includes the means to calculate an adjustment to the regulated dry runway take-off performance, particularly with the tendency to operate from runways of critical length on a higher percentage of occasions.

1.2.2 USA

In the USA the FAA has an Advisory Circular AC91-6A dated May 1978 dealing with "Water, Slush and Snow on the Runway" which provides guidelines and recommendations which suggest that take-offs should not be attempted in water, slush, or wet snow greater than 12 mm (0.5 ins), and that for lesser depths adjustment factors should be applied as described in the operations manual covering gross weight reduction, V_1 speed adjustments, and/or additional runway length required for the relevant conditions. The FAR 25 Aeroplane Design Requirements refer only to hazards related to power plant ingestion of foreign matter during take-off. The FAA plans to publish in June 1991 a rejected take-off/wet runway rule and Advisory Circular (AC) 91-6B on contaminated runways for public comment.

1.2.3 Joint Aviation Authority (JAA)

Most countries in Europe (14 to-date), including the UK, are participants in the Joint Aviation Authority (JAA) and through this arrangement contribute to forming a common airworthiness code known as the Joint Airworthiness Requirements (JARs). The countries design and certify aircraft according to the code, although some members may still continue to have their own specific differences. The specific design requirement for large civil aeroplanes are included in JAR 25 which has the USA FAR 25 as its basis, but there are differences between the two. One difference is the need for take-off performance information for contaminated runways, JAR 25X1591, Supplementary Performance Information. The requirement states that performance information must be furnished by the manufacturer in an approved document in the form of guidance material to assist the operator in developing suitable instructions when the aeroplane is operating on wet and contaminated runway surfaces, and makes provisions for the establishing of this information by analysis or test. In Amendment 88/1, effective 18.10.88 (Ref. 15), the JAA issued Advisory Material Joint (AMJ) 25X1591 providing information, guidelines, recommendations and acceptable means of compliance concerning take-off performance information on wet, standing water, slush, loose snow and compacted snow or ice covered runways. This material provides one acceptable means of showing compliance with JARX1591, but other means, including direct testing, is available for consideration.

Prior to the UK being a member of the JAA, they had amended their airworthiness standards (BCAR) as early as 1973 to require take-off performance to provide for various levels of runway aeroplane braking friction, μ, and for various depths of runway contaminates.

The U.K. Civil Airworthiness Requirements Section D requires certification of aeroplanes for take-off from precipitation covered runways. The required Take-Off Run and Take-Off Distance appropriate to the conditions should be determined and scheduled for a range of precipitation densities from 0.2 to 1.0, and shall be the all-power-units-operating configuration. Additional criteria related to handling qualities, engine ingestion protection and demonstrated performance are outlined in the requirements.

1.2.4 Canada

The Canadian Aeronautical Information Publication (AIP) October 1990 makes a reference to the application of runway friction measurements to accelerate stop distances during take-offs from contaminated runways. The problem of contaminated runway operations is described and landing distance corrections based upon James Brake Decelerometer Measurements (JBI) and Runway Surface Conditions (RSC) reports are provided in detail. The AIP includes the NOTAM (Notice to Pilots) distribution methodology. It concludes that equivalent corrections for take-off performance require further study. Nevertheless the table of RSC and JBI runway conditions is provided as a qualitative assessment of the runway surface for take-off and could assist pilots who choose to use the FAA AC 91-6A as a companion document to the Canadian adapted U.S. Airworthiness Design FARs.

1.2.5 Sweden

In Sweden, the authorities have not issued any detailed airworthiness requirements for operation on contaminated runways. Instead, they require, in their operating regulations, that runway conditions must be taken into account for the landing and take-off performance determination. Each operator has to present to the Board of Civil Aviation the procedures and the performance correction that will be applied when reduced braking action due to slush, water, snow, etc., is present. Ref. 18 and 18A provides examples of the type of information that is provided by Swedish operators and approved by the Swedish Board of Civil Aviation (See section 4.4).

1.2.6 Japan

Full scale tests on contaminated runways were carried out on several types of aircraft which provide the basis for revisions to operating manuals.

1.2.7 France

Airbus Industries adopted the JAR 25X1591 approach for the A320 which utilizes different friction coefficients for different descriptions of runway surface conditions, but decreases the 35 ft screen height to 15 ft for an engine failure "go", and retains 35 ft for all engines "go" situation.

1.3 Current Status

Airworthiness Authorities and Regulatory Agencies have recognized the lack of agreement and extensive studies have been undertaken over a period of thirty to forty years, but no universal conclusions have been reached. The U.K., U.S., Sweden and Japan have been foremost in the exploratory work, and the U.S. has more recently undertaken trials of turbo jet passenger aeroplanes on various contaminated runways and compared the braking friction with runway friction measured by ground vehicle friction measurement devices.

Also, NASA and FAA held a Runway Friction Workshop at NASA Langley Research Center, on October 26th and 27th 1988. Most experienced air transport states were represented and stressed their interest and desire to improve take-off runway friction accountability. However, Canada, like the U.S. acknowledged the lack of requirements for the use of friction data for take-off performance accountability, but did not indicate this to be a priority issue.

1.4 Objectives

This study was initiated because it was clear that there was a need in Canada to review the work of other States on take-off performance on contaminated runways to more fully identify and understand the risks during flight operations on contaminated runways, and to explore possible countermeasures for contaminated runway take-off performance.

The overall objective of the study is to improve safety in the Canadian air transportation environment. Within this context the specific objectives for this study are:

- To conduct a risk-benefit analysis for aircraft-take-off performance (rejected and continued) under wet or contaminated runway conditions;
- To identify/develop new formulae for calculating take-off performance under wet or contaminated runway conditions; and
- To identify and to evaluate the effectiveness of countermeasures in terms of reduced risk.

This study is to be completed in three phases and this report documents the results of the first phase. The objects of this first phase are to conduct the risk analysis, identify/develop new formulae for calculating take-off performance and identify countermeasures to reduce the risk of take-offs on wet or contaminated runways.

1.5 Methodology

The essential ingredients of the approach taken to improve the prediction of take-off performance during operations from contaminated runways consisted of:

- A review of the work undertaken throughout the world to understand, define, measure and describe types of runway contaminants and the relationship of the data to aeroplane take-off performance as interpreted by the manufacturers, airport operators, flight crews and regulatory authorities.
- An analysis of take-off accident/incident data on a worldwide basis where runway contamination was a contributing factor. The analysis screened all take-off accidents and developed statistics which illustrate the relative frequency of take-off accidents on contaminated runways, as well as the factors contributing to the accident, the accident severity, and the characteristics of the contaminant when included in the accident reports.
- An appreciation of the correlation of the friction measurements determined with various devices by the leading States under various contaminated runway conditions, and the reliability of the devices in comparison with the friction experienced by the aircraft.

The significance of these correlations was assessed which could signal the predictability of ground roll and braking characteristics and indicate the type and extent of future work.

- The modelling of take-off performance characteristics on dry and contaminated runways utilizing the University of Toronto Institute for Aerospace Studies (UTIAS) flight simulator computer together with B747-100 take-off performance data.
- The preparation of an estimate of the frequency of critical runway conditions based upon runway condition data at selected Canadian airports, including airport runway friction (James Brake) data and an estimate of the frequency of aeroplane take-offs at or near allowed maximum take-off weight.
- The development of a computer model to relate the results of the foregoing tasks and the probabilities of engine failure or other critical event during take-off to predicted accident risks. The model contains a risk assessment of continuing or rejecting the take-off, including both the probability of an incident/accident and the severity. The frequency of such events was calculated based upon the historical data and the take-off model which provided a realistic comparative methodology.
- A comparative analysis of the methods in use by States to describe and define runway friction as a means to determine the maturity of the methods to arrive at agreed standards which could be employed by States, operators and manufacturers. The data was obtained from the literature research, plus discussions with the Canadian Air Line Pilots Association (CALPA) and the Transport Canada Aviation Group (TCAG) and discussions during visits to foreign States.
- The identification of countermeasures available to reduce the risks was attempted based upon discussions, literature proposals and the simulator model trials. These included flight manual contaminated runway procedures based upon the proposed classification of runway conditions, changes in performance, prediction methodology, changes in critical take-off speeds and procedures, runway and tire special features, and go - no go instrumentation.

2. REVIEW OF ACCIDENTS AND INCIDENTS

2.1 Introduction

Accidents and incidents on take-off were reviewed to determine:

- the extent of the problem of take-off accidents on wet and contaminated runways;
- the relative risk of take-off accidents on dry and wet or contaminated runways;
- the types of critical events leading to take-off accidents;
- other factors contribution to take-off accidents;
- the severity of these types of accidents and other factors that contribute to the severity; and
- the potential effectiveness of various counter measures.

An aircraft accident is any event, between when persons embark or disembark the aircraft, in which a person is seriously injured or the aircraft is substantially damaged. An incident is an event, other than an accident, which affects or could affect the safe operation of the flight. For example, incidents on the take-off run include engine, instrument, electrical and tire failure or malfunction, warning light or horn activated, loss of directional control, birdstrike, etc.

2.1.1 Scope of Review and Data Sources

Initially, Canadian accident and incident data, obtained from the Canadian Aviation Safety Board, were reviewed. The accident report summaries were complete and included all the required information. However, incident reports include data only in a small number of the data fields and do not include information on the weather and runway conditions. In addition, reporting of incidents was only made mandatory for large aircraft in 1985.

Take-off accidents involving large aircraft occur very infrequently and the number of accidents in Canada provides too small a base on which to draw any conclusions. A wider base was therefore used, but only included countries where the safety level was similar to that of Canada. Barnett and Higgins (1989) showed that a good way of grouping countries with similar levels of aviation safety is into first, second and third world countries. Thus, accidents involving aircraft operated by carriers from the following countries were considered:

Canada
U.S.A.
Japan
New Zealand
West and South European countries
Scandinavian countries
Australia

ICAO maintains a worldwide aircraft accident database. It includes accidents reported by all member countries and this includes the set of first world countries considered in this study. ICAO relies on information supplied by member states and the database is not complete; some accidents are not included and little information is available on some accidents. Full accident reports must be obtained from the country reporting the accident. These were obtained for specific accidents reported by the U.S. where more information was required about the accident.

The set of accidents and incidents was restricted to that involving jet aircraft with maximum take-off weight over 5,700 kg where the aircraft was operated by carriers registered in first world countries. A 20 year (1970 - 1989) time span was used as few jet aircraft built before 1970 are still operating in Canada today.

2.1.2 Classification of Take-off Accidents and Incidents

Initially, report summaries were obtained for accidents and incidents where the first or second phase of operation (at the time of the event) was "take-off run" or "initial climb". This set was then narrowed down to include only those accidents/incidents where the initial event leading to the accident/incident occurred during the take-off run on the runway. The final event which led to the decision by the pilot to either abort or continue the take-off is known as the critical event. Accidents/incidents were included even if the critical event occurred between aircraft rotation (front wheels lifting off) and liftoff as runway condition is an important factor in the outcome of take-offs aborted at this late stage.

The set of accidents are referred to as take-off accidents, although in some cases the aircraft becomes airborne and lands or crashes later. The number of take-off accidents and incidents identified in the data sets are given in Table 2.1.

Table 2.1 Number of Jet Take-off Accidents and Incidents in Canada and in First World Countries

Type	Canadian	First World Countries
Accidents	3	84
Incidents	69	6*

* ICAO data included 6 incidents on take-off for jet aircraft

The Canadian and first world sets of accidents were compared and it was found that one of the three Canadian take-off accidents was not in the worldwide accident data provided by ICAO. This accident was therefore included in the first world set. The completeness of the ICAO accident data could not be easily verified using U.S. accident data as our request to the NTSB (National Transportation Safety Board) for a listing of the take-off accidents and accident data was referred to ICAO. The NTSB provided full accident reports for specific accidents as these are not held by ICAO.

2.2 Worldwide Accident Analysis

The set of take-off accident report summaries provided by ICAO were used to study the frequency of wet/contaminated runway accidents, the critical events, important factors and severity of accidents.

The relative accident risk of take-off accidents on dry and wet or contaminated runways is best found using the complete set of accident data together with the number of departures on dry, wet and contaminated runways. However, the ICAO accident set does not include all take-off accidents, and data on the number of departures under different runway conditions is not recorded and would be extremely difficult to estimate worldwide. Therefore, it was only possible to estimate the accident risks on wet or contaminated runways relative to the risk on dry runways.

Initially, all runway conditions were considered so that the relative risks under different conditions could be compared, and to determine if the factors involved in take-off accidents differed with runway condition.

In addition to the accidents, six incidents were included in the analysis. Five of these involved the aircraft running off the runway and in one the aircraft struck obstacles at the end of the runway. These incidents contain valuable information about safety on take-off and could easily have resulted in substantial aircraft damage or serious injuries, had the terrain and/or obstacles at the end of the runway been different. These incidents are treated as accidents for the purposes of this analysis.

2.2.1 Accident Review Methodology

The accident reports were carefully reviewed, considering both the summary fields and the narrative, to determine the following features of the accident:

- location of aircraft when the initial event occurred;
- events leading to decision to abort or continue and factors associated with those events;
- pilot action - abort, continue or no time to react before aircraft left runway;
- speed at time of pilot action relative to V_1 and V_R;
- outcome of action - aircraft stopped on runway, ran off side or end of runway (distance of overrun), or completed take-off;
- any other factors which contributed to the outcome of the pilots decision;

- weather and runway conditions;
- how and where the aircraft stopped; and
- damage to aircraft, injuries to occupants and whether damage and injury was caused by impact, fire or during evacuation.

These parameters for each accident were then entered into a data base computer file for analysis.

Take-off accidents can be grouped into a number of distinct types of accidents. The accidents types and frequency are given in Table 2.2.

Table 2.2 Frequency of Each Type of Take-off Accident - First World Countries, 1970 to 1989

Type of Accident	Frequency	
Runs off side of rwy - no time to react	2	(2%)
Abort - runs off side or end of runway	46	(51%)
Abort - stops on runway	29	(32%)
Continues take-off - runs off end of rwy	3	(3%)
Continues take-off - lift-off & crashes	4	(4%)
Continues take-off - lift-off & lands on rwy	6	(7%)

The take-off was aborted in 83% of the accidents, while in 14% of the accidents the take-off was continued after the critical event. In 2% of accidents the pilot had no time to react to the critical event before the aircraft had run off the runway.

As the effects of runway contamination and the accident severity were found to vary greatly across these accident types, analyses were repeated for each accident type in these analyses. In some cases the accidents where the pilot continued take-off were considered as a group as there were so few of these accidents. Similarly, the lost control-crash type accidents were combined with the abort-crash type accidents.

2.2.2 Frequency of Accidents on Dry, Wet and Contaminated Runways

The frequency of each type accident on dry, wet and contaminated runway conditions is shown in Figure 2.1. A third of the take-off accidents in first world countries were on wet or contaminated runways. This trend is similar in Canada where one of the three jet take-off accidents since 1970 was on a wet or contaminated runway.

Runways in Canada are wet or contaminated about a third of the time during November to March and 11% of the time during April to October (discussed in Section 5.4); thus over a full year 20% of take-offs are on wet or contaminated runways. The accident risk on wet/contaminated runway relative to dry runways can be estimated based on these runway condition frequencies and a third of take-off accidents being on runway wet/contaminated.

Let the number of departures be D and the number of accidents be A. Since the accident rate is the ratio of the number of accidents to the number of departures, the accident rate on dry and wet/contaminated runways will be:

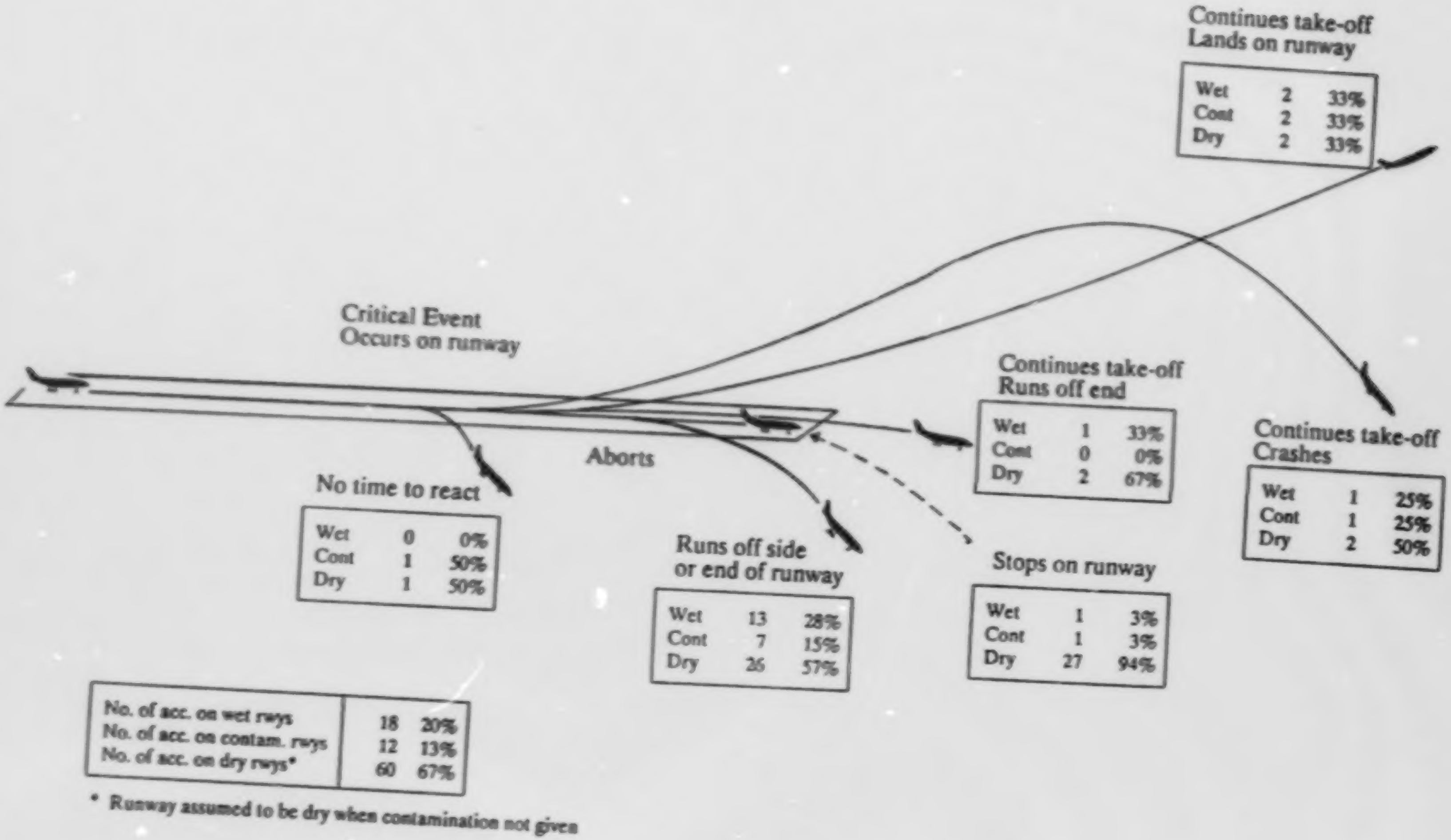
$$\text{Accident rate} = 0.33\,A / 0.2\,D \quad \text{on wet/contaminated runways}$$

$$= 0.67\,A / 0.8\,D \quad \text{on dry runways}$$

The ratio of these accident rates is

$$\frac{\text{Accident rate - wet/contam.}}{\text{Accident rate - dry}} = \frac{0.33\,A / 0.2\,D}{0.67\,A / 0.8\,D} = 2.0$$

Thus, the take-off accident risk on wet or contaminated runways is twice the accident risk on dry runways in Canada. This relative risk is only approximate as the proportion of take-off accidents on wet/contaminated runways in Canada, over a longer time period and many more take-offs, may differ from the value of a third which as found for Canada and for first world countries over the last 20 years.


Critical Event
Occurs on runway
Aborts
No time to react
Wet 0 0%
Cont 1 50%
Dry 1 50%
Runs off side
or end of runway
Wet 13 28%
Cont 7 15%
Dry 26 57%
Stops on runway
Wet 1 3%
Cont 1 3%
Dry 27 94%
Continues take-off
Runs off end
Wet 1 33%
Cont 0 0%
Dry 2 67%
Continues take-off
Lands on runway
Wet 2 33%
Cont 2 33%
Dry 2 33%
Continues take-off
Crashes
Wet 1 25%
Cont 1 25%
Dry 2 50%
No. of acc. on wet rwys 18 20%
No. of acc. on contam. rwys 12 13%
No. of acc. on dry rwys* 60 67%

* Runway assumed to be dry when contamination not given

Figure 2.1 Frequency of Take-off Accidents on Dry*, Wet and Contaminated Runways - First World Countries, 1970 to 1989

A good indication of the effect of wet and contaminated runways on the ability of the aircraft to stop on the runway is shown in Figure 2.1. Almost all of the accidents where the aircraft was able to stop on the runway occurred when the runway was dry. However, just under half of the accidents where the aircraft ran off the runway occurred when the runway was wet or contaminated. This clearly indicates that the factors causing the accidents are different under different runway conditions.

2.2.3 Critical Events on Take-off Run

The critical events which lead to the decision by the pilot to abort or to continue take-off are compared for different runway conditions in Figure 2.2. If more than one event occurred, the critical event is taken to be the final event which leads to the decision to abort or continue take-off. The type of critical event varies greatly with runway condition. On both wet and dry runways engine failure is by far the most common critical event, while on contaminated runways slow acceleration is the most common. Loss of control is more likely to be the critical event on wet and

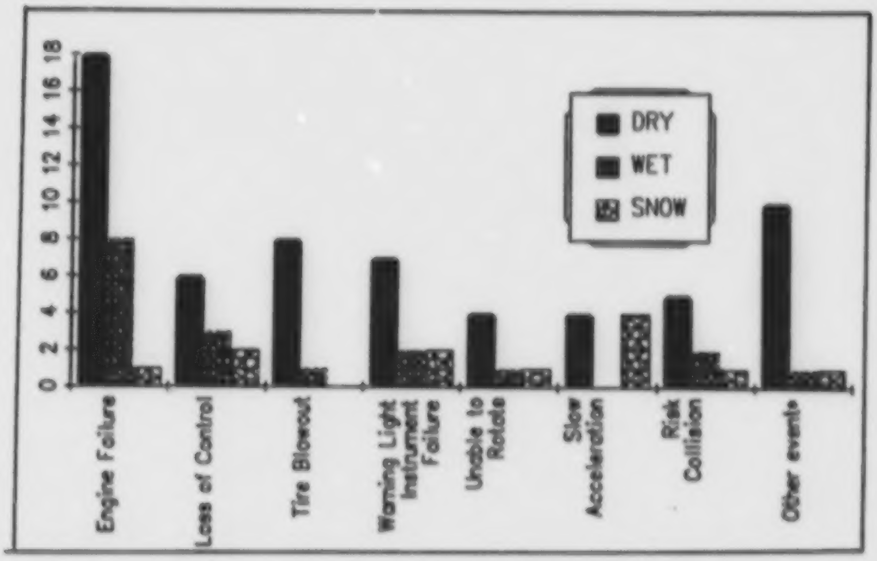


Figure 2.2 Distribution of Critical Events on Take-off Run for Dry, Wet and Contaminated Runway Conditions - Accidents in First World Countries, 1970 to 1989

* Includes severe vibration, other mechanical failure, collision with snow bank on runway, etc.

contaminated runways than dry runways while tire blowout is more likely on dry runways. Slow acceleration is usually caused by the contaminant on the runway and would therefore be expected to be a factor in accidents on contaminated runways, but not on dry runways. Similarly, the lateral friction on the tire on the runway is reduced by any contamination and this reduces the ability of the pilot to control the aircraft. Tire blowouts may be less frequent on contaminated runways partly because of the cooling effect of the water, slush or snow on the tire.

The critical events for the three main accident types are given in Table 2.3. Engine failure, loss of control, slow acceleration and warning light/instrument failure are the most common critical events which lead to an abort-crash accident. Engine failure is by far the most common critical event for abort-stop on runway accidents followed by tire failure while the critical events are spread fairly evenly for continued take-off accidents.

Table 2.3 Critical Events on Take-off Run by Outcome of Accident - First World Countries, 1970 to 1989

Critical Event	Abort-crash*		Abort-stop		Continue	
Engine failure	10	21%	15	52%	2	15%
Tire failure	3	6%	5	17%	1	8%
Slow acceleration	6	13%	0	0%	2	15%
Loss of control	10	21%	0	0%	1	8%
Unable to rotate	5	10%	0	0%	1	8%
Warning light	6	13%	2	7%	1	8%
Collision risk	1	2%	4	14%	3	23%
Other	7	15%	3	10%	2	15%
Total	48	100%	29	100%	13	100%

* Including two lost control-crash accidents

2.2.4 Speed at Time of Critical Event

The speed at which the critical event occurs and is recognized by the pilot is, of course, closely related to the accident type. The critical event speed would be expected to be less than V_1 for aborted take-offs and at or greater than V_1 for continued take-off accidents. As shown in Table 2.4, this is generally the case for continued take-off, abort-stop on runway accident and abort-crash accidents on wet runways. However, the critical event speeds for abort-crash accidents are more often greater than V_1 on dry and contaminated runways. The effect of contaminated runways is different from wet runways partly because a common critical event on contaminated runways is slow acceleration and the pilot often does not react to slow acceleration until the aircraft has used up much of the available runway. Even when the pilot acts before the V_1 speed is reached, the aircraft may not be able to stop on the runway due to the contamination. Pilots are provided with little information for detecting slow acceleration and this is one of the counter measures discussed in Section 7. Many of the abort-crash accidents on dry runways could be due to the decision to abort after the V_1 speed is reached.

Table 2.4 Aircraft Speed when Critical Event Recognized by Pilot, by Accident Type and Runway Condition - First World Countries, 1970 to 1989

Accident Type	Runway Cond.	Critical Event Speed 0 - V_1	 V_1 - V_R	 Unknown
Abort-Crash	Wet	8	3	2
	Contam.	2	5	0
	Dry	6	8	9
	All	16	19	11
Abort-stop	All	15	0	14
Continue	All	1	6	6

2.2.5 Other Factors Contributing to Accident

In most accidents a number of factors affected the success of the aborted or continued take-off. In all cases where the runway was wet or contaminated, runway condition was given as a factor in the accident. The factors, apart from runway condition, which affected the outcome varied with the type of accident and are therefore considered separately. The main factors for abort-crash accidents are given in Table 2.5. As was found with the analysis of speeds at the time of the critical event, delay in aborting take-off is a common factor on dry and contaminated runways, but not as common on wet runways. The other factors after the critical event are similar for the different runway conditions. Some form of brake failure or malfunction and pilot error are the next two most common factors in abort-crash accidents.

Table 2.5 Factors in Accident After Critical Event for Abort-Crash Accidents*

Factor	Runway Condition:			
	Wet	Contam.	Dry	Total
Delay in abort	2 (17%)	3 (43%)	9 (33%)	14 (30%)
Other human factor	2 (17%)	2 (29%)	6 (22%)	10 (22%)
Brake failure	2 (17%)	1 (14%)	5 (19%)	8 (17%)
Nosewheel steering	1 (8%)	1 (14%)	1 (4%)	3 (7%)
Other	4 (33%)	2 (29%)	2 (7%)	8 (17%)

* Percentages of accidents for a given runway condition do not add to 100 as accidents may have more than one factor. "Other" includes tire and other mechanical failure and unfavourable winds.

Most aborted take-off accidents where the aircraft stops on the runway (70%) did not have any other factors contributing to the accident. In these accidents, the critical event often leads directly to substantial aircraft damage or a fire. Brake and tire failure occurred in 10% and 7% of these types of accidents, respectively.

In continued take-off accidents, deicing was a critical factor in 2 of the three accidents on snow covered runways. Pilot error was a factor after the critical event in almost a third (4/13) of continued take-off accidents on dry and wet runways, while other factors contributed to 20% of the continued take-off accidents.

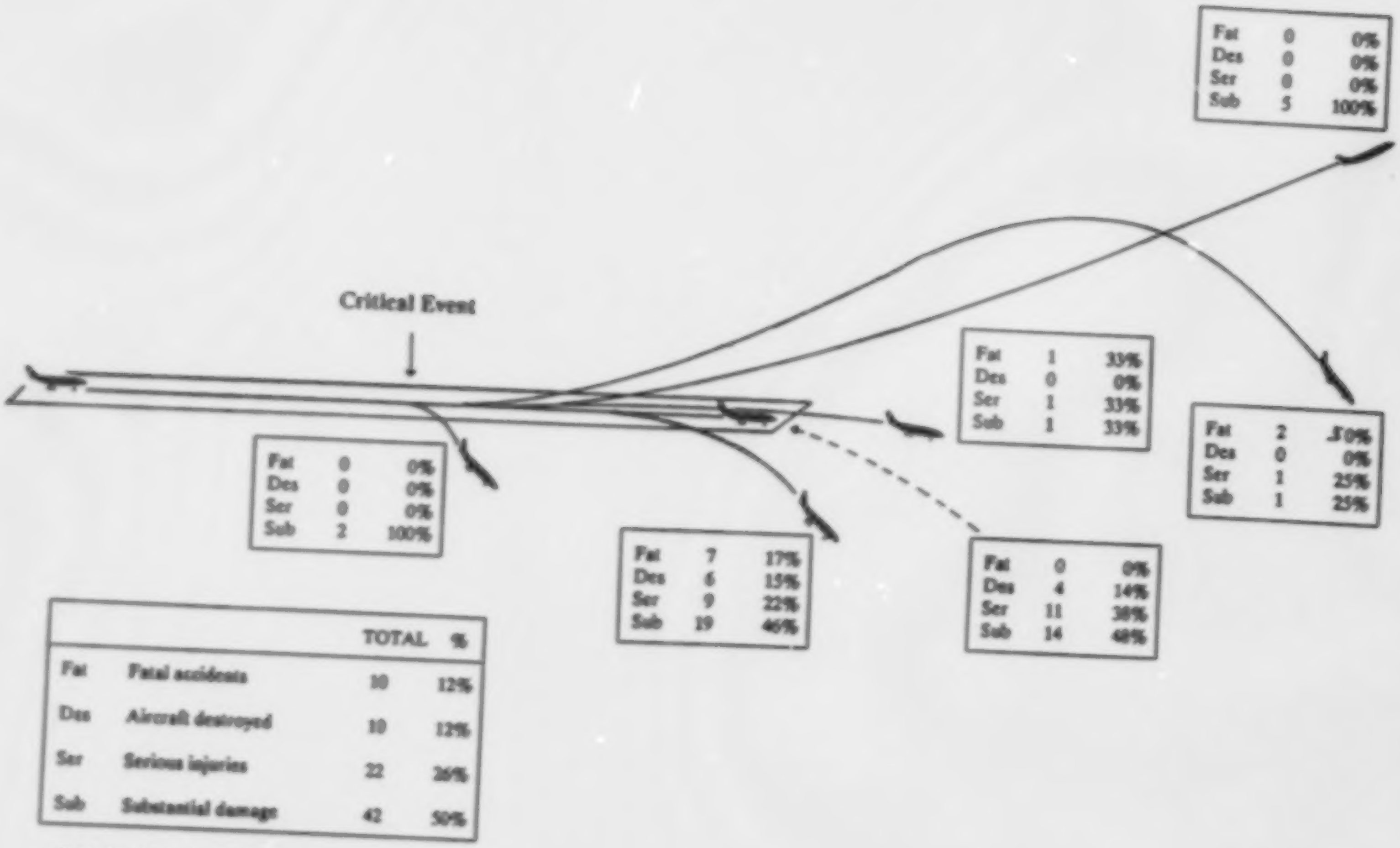
2.2.6 Severity of Take-off Accidents

The consequences of take-off accidents vary greatly with the different types of accidents as shown in Figure 2.3. The severity of the accident decreases in the following order:

Continue - liftoff - crash accidents
Continue - crash accidents
Abort - crash accidents
Abort - stop on runway accidents
Loss of control - run off runway
Continue - liftoff - land on runway accidents

One of the main factors affecting the severity of an accidents is whether a fire breaks out. Table 2.6 show the frequency of take-off accidents where a fire occurs for different runway conditions. Fire is common in accidents on dry runways with almost half of the accidents having a fire. However, on wet and contaminated runways only about 15% of take-off accidents have an associated fire. Considering accidents where the aircraft stops off the runway, the proportions of accidents with fire are still much more for dry runways, but the difference is not as great. The variation in the occurrence of fire could be due in part to the fact that many of the take-off accidents where the aircraft stops on the runway are classified as accidents rather than incidents as a result of the fire.

The severity of abort-crash accidents is very dependent on the type of terrain beyond and beside the runway. Of the 30 accidents where the aircraft overrun the runway onto flat terrain, only two involved fatalities and these were due to a fire in both cases. Four of the five fatal aborted take-off accidents on wet or contaminated runways involved the aircraft colliding with a ditch or embankment, or running into water. One fatal accident occurred when a DC10 overran the wet runway, stopped on flat terrain but caught on fire and 2 of 260 passenger died. Less than 0.3% of persons onboard during


Critical Event
Fat 0 0%
Des 0 0%
Ser 0 0%
Sub 5 100%
Fat 1 33%
Des 0 0%
Ser 1 33%
Sub 1 33%
Fat 2 50%
Des 0 0%
Ser 1 25%
Sub 1 25%
Fat 0 0%
Des 0 0%
Ser 0 0%
Sub 2 100%
Fat 7 17%
Des 6 15%
Ser 9 22%
Sub 19 46%
Fat 0 0%
Des 4 14%
Ser 11 38%
Sub 14 48%

		TOTAL	%
Fat	Fatal accidents	10	12%
Des	Aircraft destroyed	10	12%
Ser	Serious injuries	22	26%
Sub	Substantial damage	42	50%

Excludes the six take-off incidents

Figure 2.3 Frequency of the Severity of Each Type of Take-off Accident* - First World Countries, 1970 to 1989

* Excludes incidents where there were no serious injuries and no substantial damage to aircraft.

Table 2.6 Occurrence of Fire in Take-off Accidents for Different Runway Conditions - First World Countries, 1970 to 1989*

Accident Type	Fire	Runway Condition: Dry		Wet		Contam.	
All Acc.	No	32	(53%)	16	(89%)	10	(83%)
	Yes	28	(47%)	2	(11%)	2	(17%)
	Total	60	(100%)	18	(100%)	12	(100%)
Off Runway	No	21	(68%)	13	(87%)	7	(78%)
	Yes	10	(32%)	2	(13%)	2	(22%)
	Total	31	(100%)	15	(100%)	9	(100%)

* Dry runway assumed if runway condition not given; no fire assumed if no mention of fire.

aborted takeoff accidents on wet or contaminated runways were killed when the aircraft stopped on flat terrain, but 6.5% were killed when the aircraft ran into a ditch, embankment, other obstacle or water. The risk is therefore 25 times greater in the latter case.

2.3 Canadian Accident and Incident Data Analysis

2.3.1 Take-off Accidents in Canada

There have been three take-off accidents in Canada since 1976. These are briefly described below:

- 1978, Toronto, DC-9 - Take-off aborted due to a tire failure which caused a gear unsafe light to go on at about 10 knots below V_1; aircraft overran runway due to excessive delay in abort. There was some moisture on the runway, but runway condition was not given as a factor in the accident. Two passengers were killed and 47 were seriously injured.

- 1984, Calgary, B737 - the aircraft successfully aborted the take-off after an engine failure, but the aircraft was destroyed by fire on the taxi ramp. Four passengers received serious injuries while evacuating the aircraft.

- 1986, Wabush, B737 - Engine failure at about V_1 due to birdstrike, take-off aborted and aircraft ran off end of runway due to hydroplaning on wet runway. The aircraft was at maximum take-off weight for that runway. The aircraft was substantially damaged, but there were no injuries.

Wet or contaminated runway was a factor only in the accident in 1986 at Wabush. This accident is well documented in CASB Report number 86-A60024. The number of Canadian take-off accidents is too small to analyze separately for the purposes of this review: these accidents were analyzed in conjunction with the worldwide accident data (Section 2.2) and with the Canadian incident data below.

2.3.2 Incidents on Take-off in Canada

The incident reports have been collected since 1976, but reporting has been mandatory for aircraft with maximum take-off weight over 5,700 kg only since in 1985. Almost all jet aircraft in Canada have a maximum take-off weight over 5,700 kg and are therefore subject to mandatory reporting.

Incident report summaries obtained from CASB were reviewed and classified by the type of critical event recognized by the pilot on the take-off run and the action taken. Where more than one event occurred, the final event leading to the decision to abort or continue take-off was designated the critical event. Incidents involving birdstrikes where there was no damage to the aircraft or action taken by the pilot were not considered, as a birdstrike alone is not likely to cause an aborted take-off. Between 1976 and 1989, 118 incidents with critical events were reported on the take-off run for jet aircraft.

The yearly distribution of reported incidents for jet aircraft is shown in Table 2.7. Prior to 1986 reporting of these incidents was clearly spasmodic and the CASB confirms that the data is incomplete for the early years. Since 1986 the reporting appears to have stabilized, but it is not known if all incidents are being reported. The analysis is based on reported incidents from 1986 to 1989.

Table 2.7 Reported Incidents with Critical Events on Take-off Run for Jet Aircraft in Canada from CASB

Year	Engine Failure	Tire Blowout	Warning Light*	Other	Total
1976	0	1	0	0	1
1977	0	0	0	1	1
1978	1	6	0	1	8
1979	0	3	0	1	4
1980	1	6	0	1	8
1981	1	1	0	0	2
1982	0	1	0	0	1
1983	1	0	0	0	1
1984	5	2	0	2	9
1985	3	4	2	2	11
1986	7	4	1	8	20
1987	5	2	8	7	22
1988	4	2	3	1	10
1989	9	5	2	4	20
Total 1976-89	37 (31%)	37 (31%)	16 (14%)	28 (24%)	118 (100%)
1986-89	25 (35%)	13 (18%)	14 (19%)	20 (28%)	72 (100%)

* Includes instrument and electrical failure/malfunction

2.3.3 Critical Events in Incidents

Engine failure is the most common critical event (see Table 2.8) accounting for almost a third of the total number of events. The occurrence of tire failure appears to have declined over the last ten years. Some form of warning light or instrument or electrical failure made up almost a fifth of the critical events since 1985. Other events, such as risk of collision, severe vibration, smoke, malfunction of other parts of aircraft excluding engine failure, account for the remaining 28%.

The Canadian incident reports include little circumstantial data and do not give the runway condition or, in most cases, the weather conditions. Therefore, the occurrence of critical events on take-off could not be linked to the runway conditions.

The actions taken by the pilots in response to the different types of critical events are given in Table 2.8. Engine failure and warning light/instrument or electrical failure were the most common critical events in aborted take-offs, but tire failure, loss of directional control and other events were more frequent in continued take-offs. The difference could be due to the time of occurrence (before or after V_1) or due to a lower perceived safety risk of the latter group of events. The speed at which the critical event occurred is rarely given so it is not possible to determine the extent of each of these causes.

Table 2.8 Response by Pilot for Incidents on Take-off Run - Jet Aircraft Incidents Reported to CASB, 1986 to 1989

Critical Event	All Incidents	Abort	Continue
Engine Failure*	25 (35%)	22 (47%)	3 (12%)
Warning light	14 (19%)	13 (28%)	1 (4%)
Tire Failure	13 (18%)	3 (7%)	10 (40%)
Loss of control	5 (7%)	1 (2%)	4 (16%)
Birdstrike #	5 (7%)	4 (9%)	1 (4%)
Other	10 (14%)	4 (9%)	6 (24%)
Total	72 (100%)	47 (100%)	25 (100%)

[*] Four engine failures were initiated by a birdstrike, 3 of which resulted in aborted take-offs.

[#] Birdstrikes which caused no damage and no real safety threat were not included.

The pilot aborted the take-off in response to the critical event in 65% of the take-offs. This varies with the type of event as shown in Figure 2.4. Therefore, all critical events cannot be treated the same when determining the likely pilot response and outcome of the critical event.

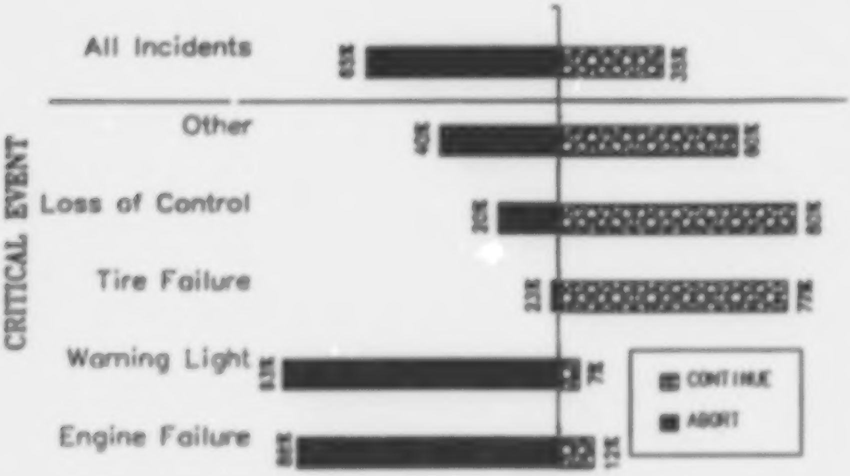


Figure 2.4 Percentage of Take-offs Aborted and Continued for Each Type of Critical Event

2.4 Accident/Incident Analysis Findings

2.4.1 First World Countries

- There have been 84 take-off accidents involving jet aircraft of first world countries since 1970, including three accidents in Canada. In addition, there were six aborted take-off overrun incidents in first world countries reported to ICAO where only minor injuries or aircraft damage was sustained.
- Of these accidents, 83% were aborted take-off accidents, and 20% were on wet or water covered runways and 13% on snow, slush or ice covered runways.
- Of the aborted take-off accidents, the runway was wet or contaminated in only 6% of accidents where the aircraft stopped on the runway, but was wet or contaminated in 43% of accidents where the aircraft left the runway.

- Engine failure is by far the most common critical event on dry and wet runways, while slow acceleration is the most common critical event on contaminated runways. Loss of control is more common on wet and contaminated runways and tire blowout is more common on dry runways.

- For abort-run-off-runway accidents, the decision to abort the take-off due to a critical event which occurred after the V_1 speed is much more common on dry than on wet runways. A late decision to abort is also common on contaminated runways due to a common critical event being slow acceleration.

- The most common other factors associated with abort-run-off-runway accidents are pilot error and brake failure, and deicing is a critical factor in continued takeoff accidents on snow covered runways.

- 11% of the take-off accidents involved fatalities, the most severe accidents being continued-take-off-crash accidents.

- The occurrence of a fire usually increases the severity of the accident and fire is common in aborted take-off accidents on dry runways, but is relatively uncommon on wet or contaminated runways.

- The severity of aborted take-off accidents on wet and contaminated runways is usually low when the aircraft stops on flat terrain, but can be high when the aircraft runs into a ditch, embankment, other obstacle or water.

2.4.2 Canadian Accidents and Incidents

- In Canada the take-off accident risk on wet or contaminated runways is approximately twice the risk on dry runways based on runway condition frequencies in Canada.

- About 12 jet aircraft take-offs are aborted per year in Canada, half of these due to engine failure.

- About 6 take-offs per year are continued after some critical event; tire failure comprises 40% of these critical events and engine failure only 12%.

3. RUNWAY FRICTION CHARACTERISTICS AND MEASUREMENT

The types of contamination which an aeroplane may encounter during take-off are:

Water
Slush (snow and water)
Snow, wet or dry
Ice

Prior to providing a more detailed description of these contaminants and their interrelationships, the characteristics of dry runway surface conditions requires review because the interaction of the contaminant with the dry runway surface characteristics is often a hidden factor in seeking agreement on runway surface conditions.

3.1 Dry Runway Friction Characteristics

The classic definition of coefficient of friction is the ratio between the tire friction force and the vertical load acting on the tire. A wheel/tire which is rolling has zero slip as compared with a locked wheel which has 100 percent slip since the tire at its point of contact with the ground has zero speed. The slip of a braked unlocked wheel is directly proportional to the ratio of the peripheral speed of the braked tire versus the peripheral speed of the rolling tire, each at point of contact with the ground and is expressed as a percentage.

The friction force produced by the wheel/tire surface contact varies with the percentage slip, but the relationship of friction to slip is dependent upon tire pressure, surface roughness, and ultimately on the type of contamination on the surface. However, because this discussion is focussed upon dry surfaces the influence of contaminants will be excluded and discussed later after the dry friction characteristics have been fully described.

Figure 3-1 illustrates the relationship of the Coefficient of Friction μ versus percent slip. This does not represent actual data but is illustrative of the phenomena. The maximum value of μ which could range from ten to twenty percent slip

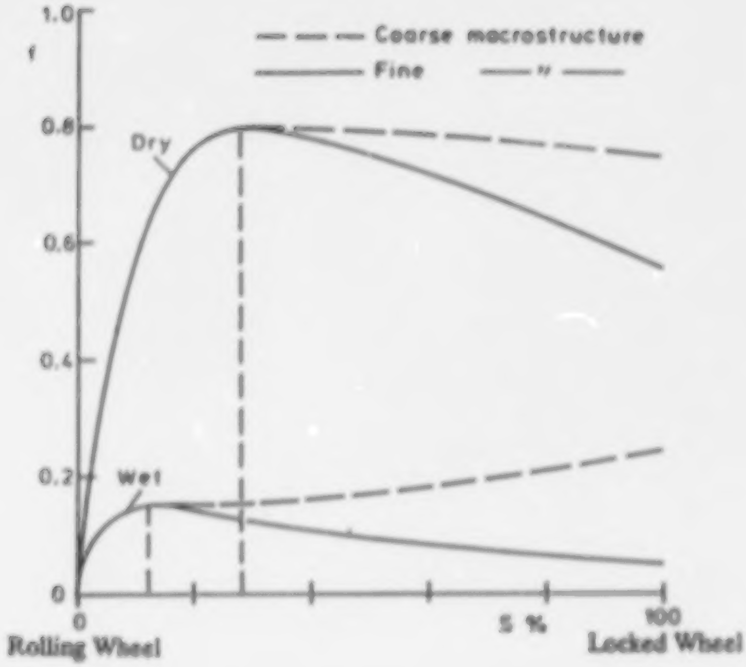


Figure 3.1 Brake Number vs. Slip Ratio in Principle

Source: Ref. 50, Fig. 11, Page 53

is caused by tire flexure which is tire pressure-dependent for a given tire, and is the value at which anti-skid brakes are designed for maximum efficiency. It is also a function of wheel peripheral speed, runway surface texture and condition, tire pressure, and ambient temperature, and can be measured. Therefore, an understanding of the μ-slip relationship is significant for measuring runway surface friction, and for determining aeroplane runway friction characteristics, and the correlation between the two.

3.2 Runway Surface Texture

To better understand the variables which influence the correlation between the friction test devices and the aeroplane braking performance it is worth considering dry runway surface variabilities. The concepts of microstructure and macrostructure characterize the friction and drainage aspects of a runway.

Microstructure, also known as microtexture, refers to the texture or roughness of individual stones which may be smooth or of a grit-like (harsh) nature. Adhesion friction is greater for a rougher surface and when the surface is wet the difference in adhesion friction is even greater for a rough surface than for a smooth surface.

Macrostructure refers to aggregates which may be fine (closed) or coarse (open) and which are large compared with microstructure, but which are small compared with a tire footprint. Hysteresis friction involves the deformation of rubber when the tread slides on the runway surface and the resulting horizontal force increases with sliding speed which is the opposite of an adhesion horizontal force. Figure 3-2 illustrates the two friction characteristics and their total effect on a dry hard surface.

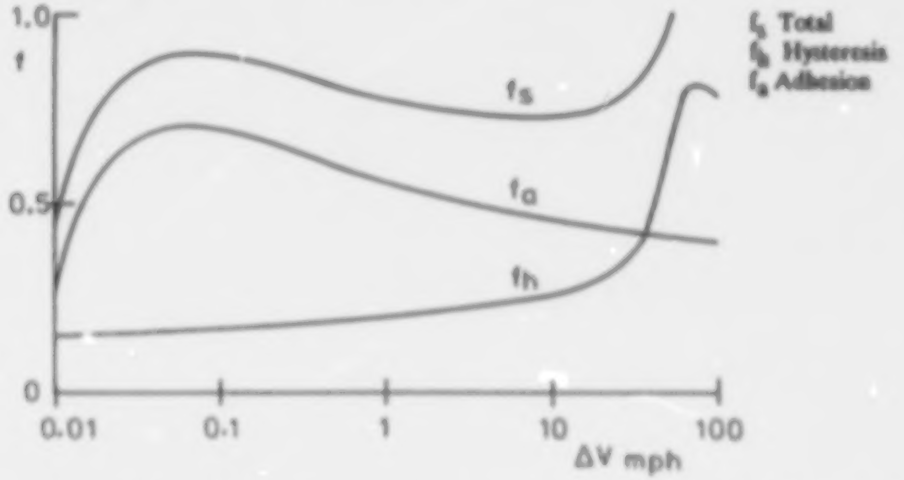
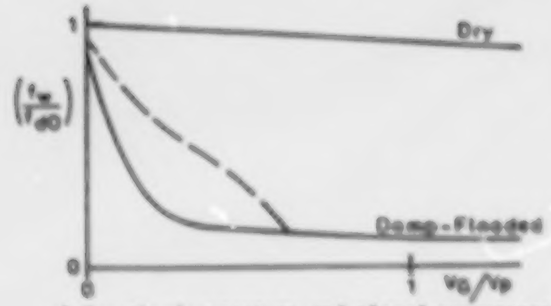


Figure 3.2 Adhesion, Hysteresis And Total Frictional Numbers When A Rubber Block Slides Along a Dry Hard Surface

Source: Ref. 50, Fig. 4, page 47

Dust, rubber deposits, and paint can mask the microstructure of a runway but do not influence the macrostructure unless combined with water, oil, fuel, thin ice or hoar frost.

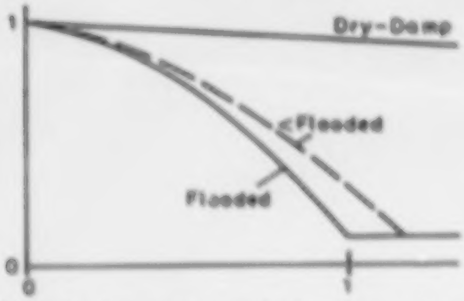
Figure 3-3 illustrates the friction number or brake number versus speed for various combinations of microtexture and macrotexture for dry and dry-damp conditions; there is little difference. However, for damp-flooded and flooded conditions the differences are impressive.



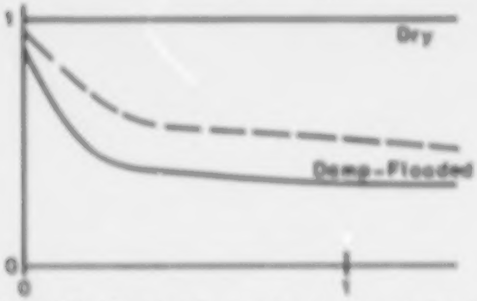
a) Smooth microtexture and closed macrotexture

$$\frac{f_w}{f_{d0}} = \frac{\text{brake number wet}}{\text{brake number dry at } V_G = 0}$$

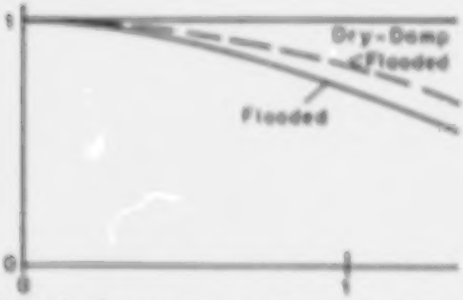
$$\frac{V_G}{V_P} = \frac{\text{Ground Speed}}{\text{Dynamic Planing Speed}}$$



b) Harsh microtexture and closed macrotexture



c) Smooth microtexture and open macrotexture



d) Harsh microtexture and open macrotexture

Figure 3.3 Brake Number vs Speed on Differently Textured Runways

Source: Ref. 50, Fig. 7, Page 49

The full explanation may be found in Ref. 50 and can be summarized by the following:

- Figure 3.3(a) Smooth micro and closed macro textures are unlikely in practice, hence the dotted curve is more likely and only very shallow water is necessary for viscous or dynamic hydroplaning.* Slush and wet snow may cause viscous hydroplaning at low speeds particularly if the temperature is around the freezing point. If the ice is dry then relatively high brake numbers are possible. However, loose sand, dust, mud with small amounts of water are very slippery, and brake numbers are low.

- Figure 3-3(b) Harsh micro and closed macro textures produce partial to total dynamic hydroplaning depending on water depth, and little viscous hydroplaning unless slush or wet snow exist.

- Figure 3-3(c) Smooth micro and open macro textures are usually found to be more semi-harsh in practice which accounts for the dotted curve as long as the braked velocity is less than hydroplaning velocity. Viscous hydroplaning may occur if slush or wet snow exist, or with dust or mud and light rain.

- Figure 3-3(d) Harsh micro and open macro textures are best able to prevent total hydroplaning and are the preferable runway surface to suppress viscous and dynamic hydroplaning.

Reference 50 also includes data from pilot reports of brake numbers on landings on 23 runways of varying age and surface texture under various contaminate conditions and these reports are compared with the measured brake numbers. Figure 3-4 shows the variation in results as a percentage of the variation of the measured friction and the pilot estimated friction.

The greatest differences occurred when the brake numbers became speed dependent, which is a direct function of the existence of loose contaminants, or slush, or mud and light rain, or oil, or paint, or rubber, and a temperature about freezing on surface textures which are less than harsh micro and open macro. The speed difference between the ground vehicle at 30 to 120 km/hr and the landing speed of the aeroplane accentuate the brake number speed contribution to the test result variations between the ground vehicle and aeroplane.

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* Hydroplaning is described in 3.3.1.

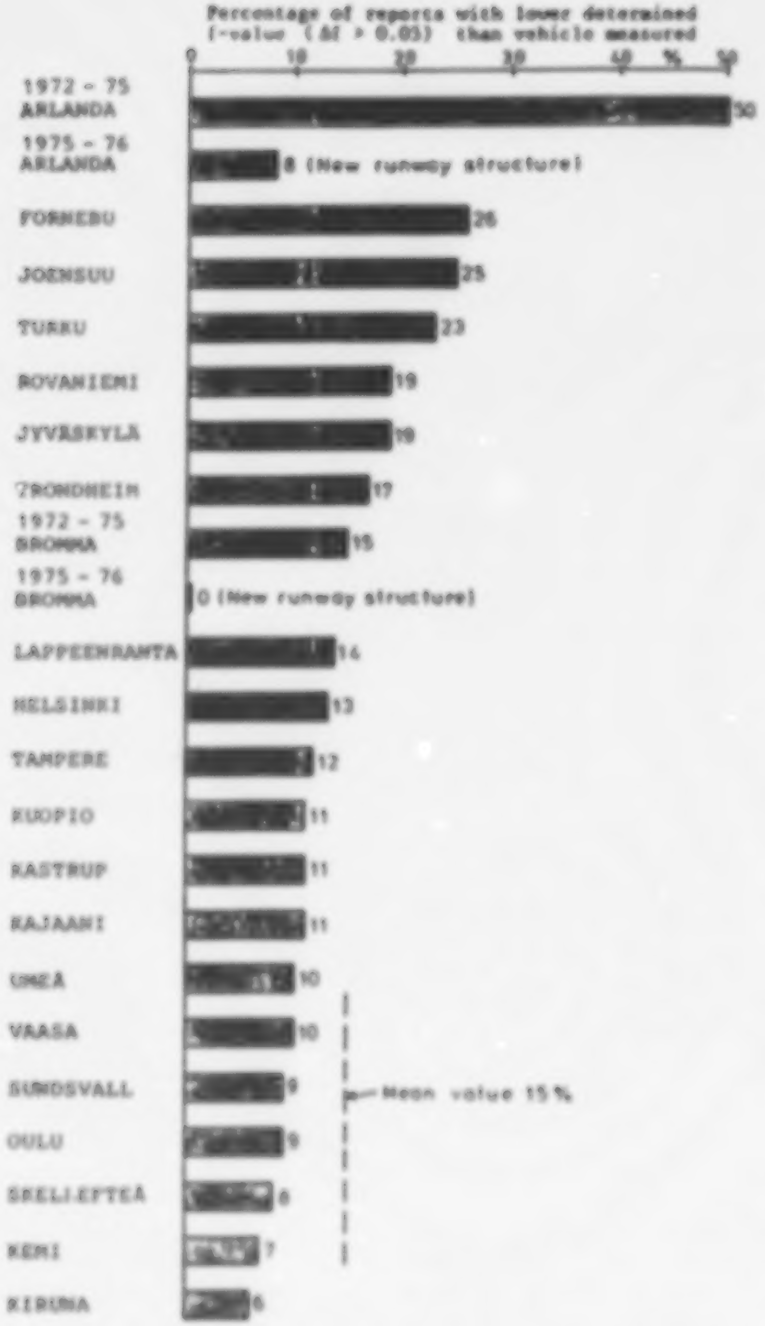

Figure 3.4 Results from the Pilot's Report Investigation 1972-76. Total Number of Reports 8696, Number of Complaints 1276 (15%)

Source: Ref. 50, Fig. 8

Other variables which are significant include tire tread design, tire pressure, variability of the runway surface condition throughout the braking run which reduces the effectiveness of anti-skid brakes, cross-wind, runway crown and side slope. Further discussion of these results in Section 3.3.3 will focus on the correlation problems between ground friction measurements and those experienced by the aeroplane.

3.3 Types of Contaminants

The characteristics of runway contaminants have been assembled from a number of sources in the bibliography which contained sufficient similarity to offer uniformity if not consensus. Each condition is discussed together with a description of the impact upon an aeroplane in the process of accelerating or decelerating.

3.3.1 Water

Water contamination in general changes the friction characteristics compared with a dry surface because the tire displaces the water in order to contact the surface. The area of contact varies according to the depth of water, tire pressure, surface texture, and thus the friction force depends upon the area of contact between the tire and the surface.

The four types of runway conditions associated with water and the generally accepted range of the depths of water are damp, wet, flooded and ponding as defined in box below.

Damp -	0 to 0.2 mm	surface does not glisten
Wet -	0.3 to 2.5 mm	surface glistens but is not flooded
Flooded -	2.6 or more mm	caused by rain >30 mm/hr
Ponding -	> 2.6 mm	due to runway concavities

The impact of water is considerable and is discussed below.

Viscous Hydroplaning usually occurs on smooth micro and closed macro textures. It is due to the fact that the tire contact area with the surface is negligible or non existent because of a thin film of water. The tire tread is important in overcoming the water viscosity because it helps to displace the water. Ref. 50 indicates that "viscous planing only occurs on very smooth and fine grained surfaces and that a macrotexture depth of approximately 0.3 mm is sufficient to prevent such planing.

Dynamic Hydroplaning. When water depth exceeds the macrostructure and the speed of the tire is high enough to prevent the tire from displacing the water film, the water pressure in front of the tire penetrates further under the tire and causes it to plane. The speed at onset is proportional to the square root of the tire pressure.

3.3.2 Slush

Slush is a mixture of snow and water with a temperature at or about the freezing point. The density is typically 10% to 20% less than that of water, but the viscosity is greater than that of water, and increases as the proportion of water decreases.

Slush Planing occurs similar to viscous planing and dynamic planing but at higher speeds. During take-off a further effect is manifested from slush, namely increased slush displacement drag and impingement of the spray on the airframe. These characteristics will be discussed in Section 4.2 on take-off performance.

3.3.3 Snow

Dry and loose snow which has a specific gravity less that 0.35 is usually blown free by the wheels. Wet snow, specific gravity of 0.35 to 0.5, is similar on a smooth surface to a wet smooth surface. Compact snow at temperatures below freezing remains dry, but a water film can be caused by tire pressure and rolling friction which then becomes similar to a smooth wet surface. This does not hold if the water film turns to ice.

3.3.4 Ice

Dry ice alters the texture to that of a smooth surface and due to tire pressure can become wet, dependent upon the surface temperature.

Wet ice accentuates the smooth surface characteristics.

3.3.5 Urea, Sand and Other Contaminants

Urea, which is used for ice control, when applied at too low an ambient temperature (i.e less than $-9.5^{\circ}C$) can give rise to urea slush which impedes braking, and which is detrimental to take-off performance.

Sand can improve friction on ice, but if it has impurities which give rise to mud when wet, it can detract from the advantages of harsh and open textures.

Oil and fuel patches give rise to spotty conditions which cause anti-skid systems to be less effective. This problem probably relates to the combination of contaminants as well.

Rubber which can give rise to reverted rubber planing, only occurs on landing and will not be discussed in this report because during take-off the need for accelerated wheel spin-up does not exist. During accelerate-stop the aeroplane may encounter rubber coating on the runway surface but this would happen over a short length of runway, at reduced aeroplane velocity, and would not involve non-rotating wheels.

3.4 Runway Friction Test Devices

3.4.1 General

Runway friction braking action is required to provide:

- deceleration of the aeroplane after landing or during a rejected take-off;
- directional control during ground roll on take-off or landing or during a rejected take-off in the presence of a cross-wind, engine failure, and other malfunctions; and
- wheel spin-up at touchdown.

Thus the problem of assessing runway friction in terms meaningful to the pilot is essential and has been attempted by means of friction test devices which are intended to be representative of aeroplane braking characteristics during landing or rejected take-offs.

The ICAO Airport Services Manual Doc 9137-AN898, Part 2 Pavement Surface Conditions, 1984, Chapter 5 describes in detail the many types of Friction Test Devices and their properties. Table 5-1 of that report contains the properties of nine types of equipment and is reproduced in this report as Table 3-1. Chapter 5 is provided in Appendix A with full description of the equipment.

3.4.2 Test Equipment Correlation

Several authors have reported on the correlation between Friction Test Devices in addition to ICAO, and specific test programs were conducted in the U.S., France, U.K., Sweden and Japan to demonstrate the correlation between specific Test Devices and aeroplanes under controlled runway conditions and during commercial operations at several airports.

The ICAO Airport Services Manual, Chapter 5 reports that the "friction measuring equipment readings do not correlate with each other on all wet surfaces. This is because each vehicle measures something different. All have different tires, some are attempting to measure skid, some measure a constant slip ratio, some measure side force, some measure at constant speed and some range of speeds, and so on. The correlation of friction measuring equipment on snow or ice-covered surfaces, although not adequate, is substantially better than on wet surfaces".

Figure 3.5 taken from Chapter 5, Figure 5.1 illustrates the correlation for snow or ice-covered runways between the:

Diagonal Braked Vehicle (DBV)
James Brake Decelerometer (JBD)
Skidometer (SKIDO)
Surface Friction Tester (SFT)
Mu-Meter (MU-M)
Tapley Meter (TAP)

Table 3.1 Characteristics of Runway Surface Test Devices

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Source: ICAO Doc 9137-AN/898, Table 5.1

Table 3.1 Characteristics of Runway Surface Test Devices (Continued)

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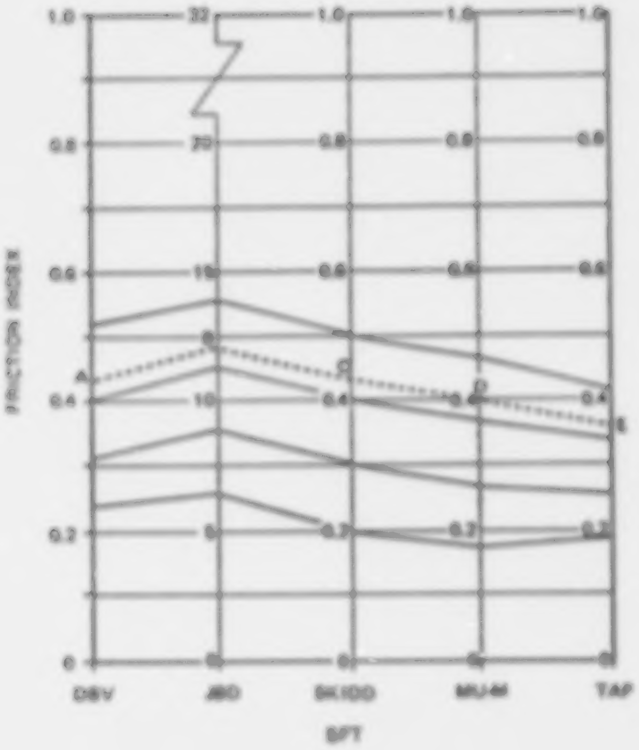
Source: ICAO Doc 9137-AN/898, Table 5.1



DBV values are shown as the reciprocal of the wet-to-dry stopping distance ratio.

Figure 3.5 Friction Test Device Correlation Chart for Compacted Snow- or Ice-covered Surfaces

Source: ICAO Doc 9137-AN/898, Fig. 5.1

At the time of the publication of the ICAO Airport Services Manual in 1984, the conclusion reached was that "there is no direct and simple correlation between the readings of these devices and aircraft stopping performance on wet surfaces".

However, Ref. 56, released in February 1990, "Summary of Test Results from Joint FAA/NASA Runway Friction Program" is much more optimistic about the correlation between estimated aircraft braking performance and the measured values except for some rain-wet data. The test program included the B727 and B737, several types of ground test vehicles and a total of 1200 test runs of which 200 were aeroplane tests, on all types of contaminants.

In fact the Major Test Findings state in part:

- "A reasonable method of estimating aircraft tire wet, snow-covered and ice-covered runway braking performance from different ground vehicle friction measurements has been established and available data show good agreement".

- "Speed, water depth, surface type and texture, tire tread design, inflation pressure, and test operating mode were identified as major factors that influence wet-runway tire friction performance".

- "The ground vehicle and aircraft tire friction correlations derived from the available wet runway data suggest that the friction relationships change with surface water depth".

- "Aircraft and ground vehicle friction measurements showed little influence of speed and type of surface for dry runway condition".

- "With proper maintenance, equipment checkout, and instrument calibration performed on a regular schedule, each ground friction measuring device operated satisfactorily and produced consistent, repeatable, and accurate friction data".

- "Tire friction measurements should be obtained for a range of rainfall rates on a given runway to identify the influence of surface water depth".

- "The range of friction values measured by the different ground vehicles under compacted snow- and ice-covered runway conditions could reasonably be divided into four distinct levels of braking action - excellent, good, marginal and poor".

- "Ground-vehicle friction measurements have been shown to correlate with aircraft tire friction data; consequently, vehicle friction data collected under adverse weather conditions should be routinely reported to all air traffic using the airport facility".

- "Proper and timely use by airport operators of snow and ice removal equipment and chemical treatments is essential to restore runway friction levels to near-dry surface performance as soon as possible".
- "Widespread usage of ground-vehicle friction measurements is strongly recommended for runway surface maintenance and is a valuable tool for monitoring current runway friction conditions".

Figures 3.6 to 3.12 from the NASA report are excellent illustrations of friction data for the runway test equipment, and the 727 and 737 aeroplanes on specific types of runway surface conditions.

Figure 3.11 is basically the same as Figure 3.9 with the B737-B727 friction data added. An additional Figure 3.12 has been prepared to compare the NASA (Ref. 56) data with that of the ICAO data in Figure 3.5. The points which were transposed to Figure 3.12 indicate that there is good correlation between the NASA and ICAO data. Figure 3.13 was included to illustrate the data from Ref. 47 which is an interim report on the test work of Ref. 56. This data is also plotted on Figure 3.12 and shows that final data for the BV-11 predicts lower friction values, than that of Ref. 56. Note that Ref. 56 scale for RCR was altered from that ICAO (Fig. 3.5) and Ref. 47 (Fig. 3.13).

The comparative friction data for the B727, B737 and runway test equipment given in Figures 3-14 and 3-15 indicates that the aeroplane friction values are usually much less than the test equipment and often less than half those of the test equipment. The ratio is about one half for dry runway based on data provided in Figures 3.14(a) and 3-15(a) for the B737 and B727 respectively. The dry/snow ratios are modestly comparable for the aeroplanes and test equipments and of the order of 5 to 1, for the dry/ice ratio, of the order of 4 to 1 for packed snow on ice for both aeroplanes and test equipments, but on glare ice the aeroplane is 20 to 1 while the test equipment remains at 4 or 5.

The concept of comparing dry/contaminated ratios has merit and was utilized effectively in 1965 during a series of tests conducted by USAF-NASA team with a C141A four-engined jet transport and several instrumented ground vehicles on 50 runways in the U.S. and Europe under dry, wet, flooded, slush,

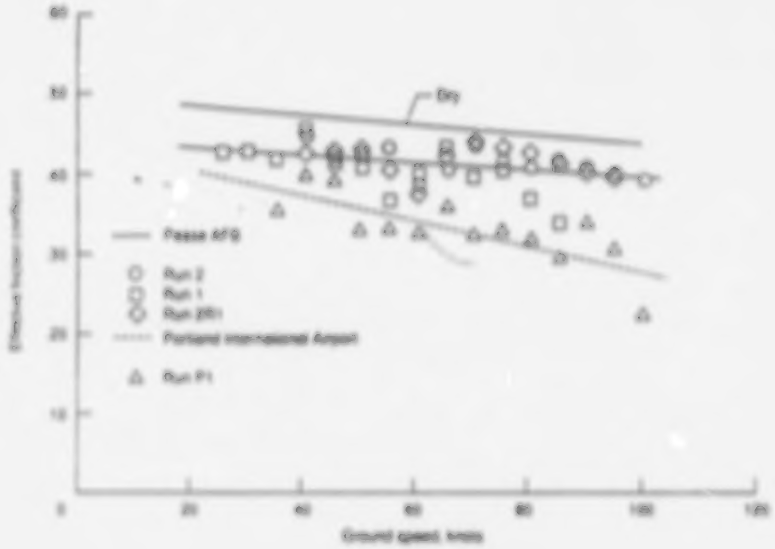


Figure 3.6 Boeing 727 Aircraft Braking Friction Performance Obtained on Rain-damp Porous Friction Course Runway Surfaces

Source: Ref. 56, Fig. 69

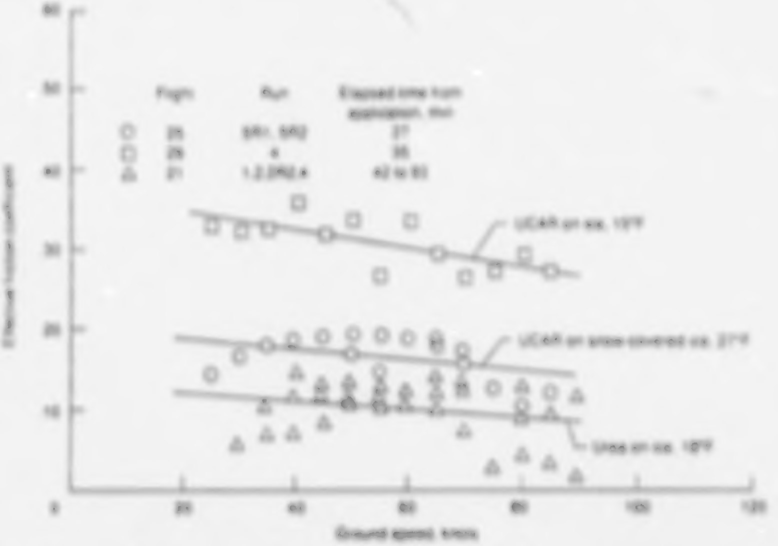


Figure 3.7 Effect of Runway Chemical Treatment Type and Elapsed Time on Boeing 727 Tire Friction Performance on Ice-covered Runway at BNAS

Source: Ref. 56, Fig. 70

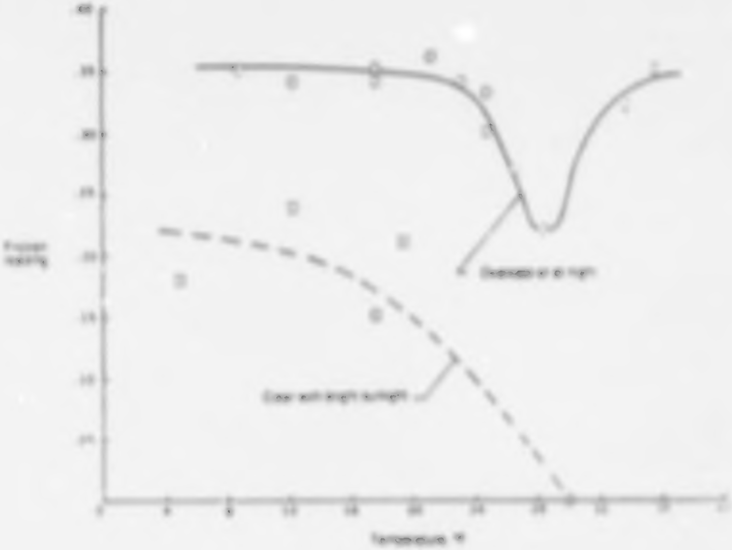


Figure 3.8 Temperature Effect on Tapley Meter Friction Measurements Obtained on Compacted Snow- and Ice-covered Surfaces on U.S., Canadian, and Swedish Runways with Several Vehicles

Source: Ref. 56, Fig. 71

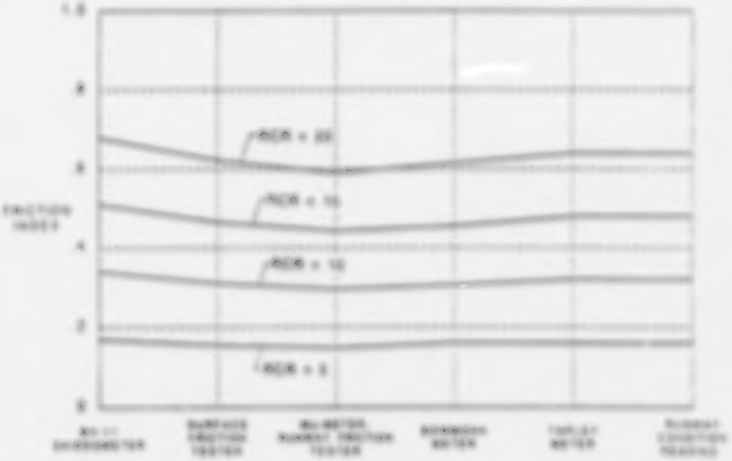


Figure 3.9 Ground-vehicle Friction Correlation for Compacted Snow- and Ice-covered Runway Conditions. (Maximum Friction Index Value of 1.0 Equals RCR of 32)

Source: Ref. 56, Fig. 3.9

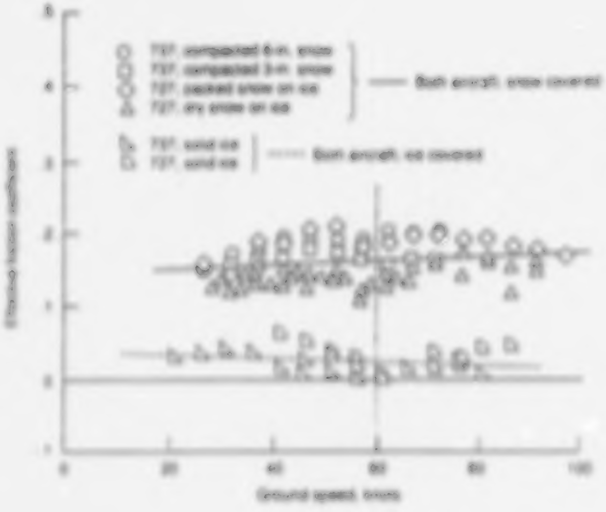


Figure 3.10 Comparison of Boeing 737 and 727 Braking Performances on Compacted Snow and Ice-covered Runway Surfaces at BNAS

Source: Ref. 56, Fig. 73

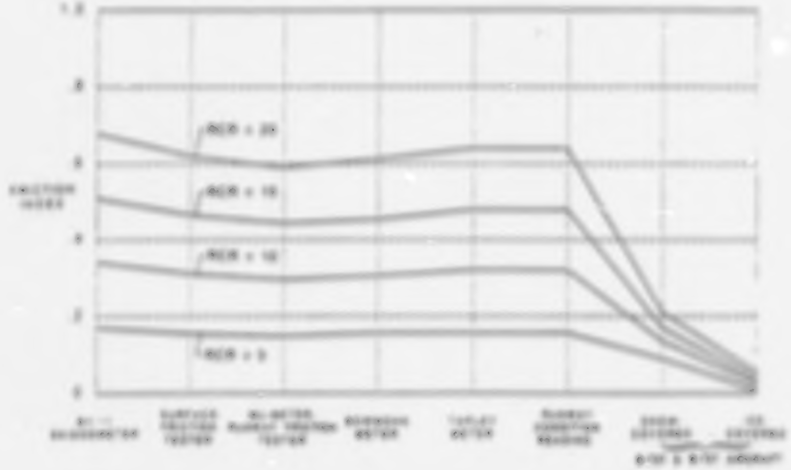
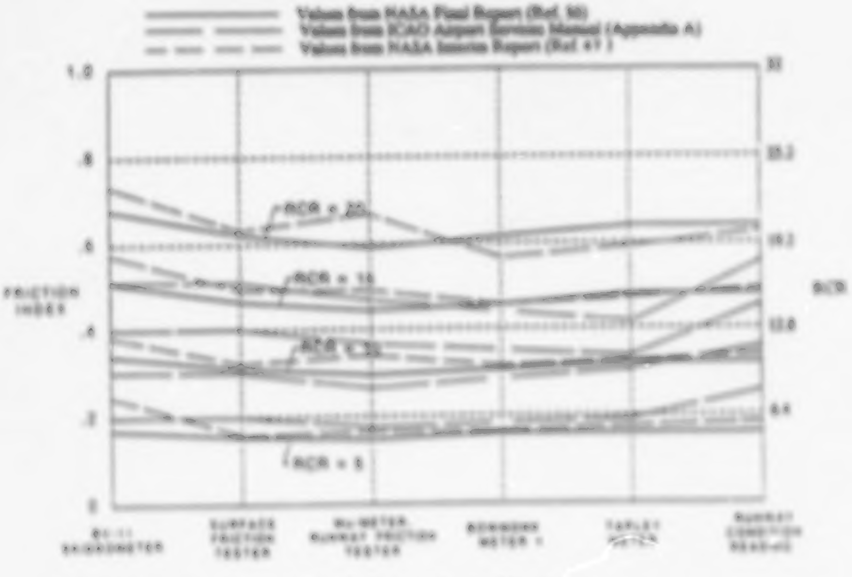


Figure 3.11 Aircraft and Ground-vehicle Correlation for Compacted Snow and Ice-covered Runway Conditions. (Maximum Friction Index Value of 1 Equals RCR of 32)

Source: Ref. 56, Fig. 74



* No values for Bowmonk meter given in ICAO Airport Services Manual

Figure 3.12 Ground-vehicle Friction Correlation for Compacted Snow- and Ice-covered Runway Conditions. (Maximum Friction Index Value of 1.0 Equals RCR of 32)

Source: Ref. 56, Fig. 72

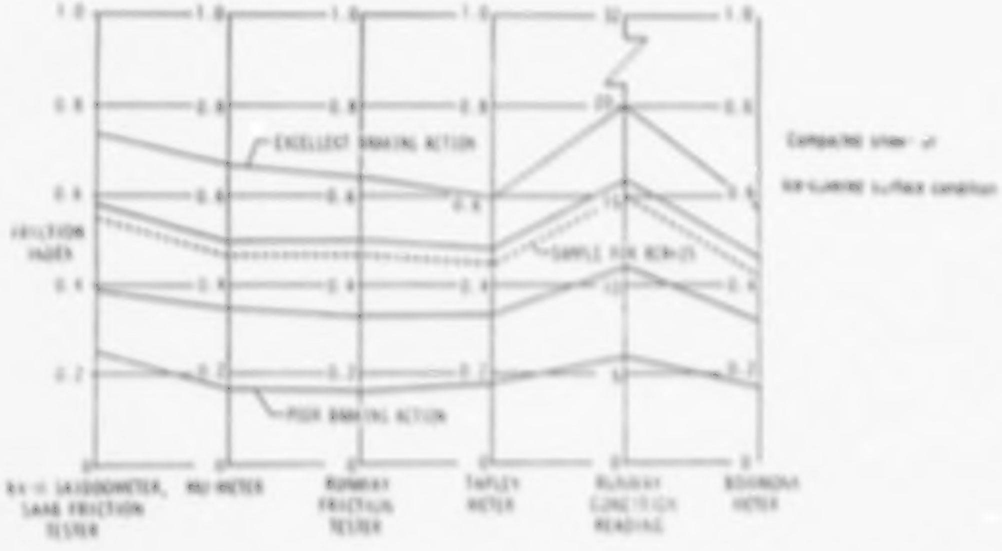
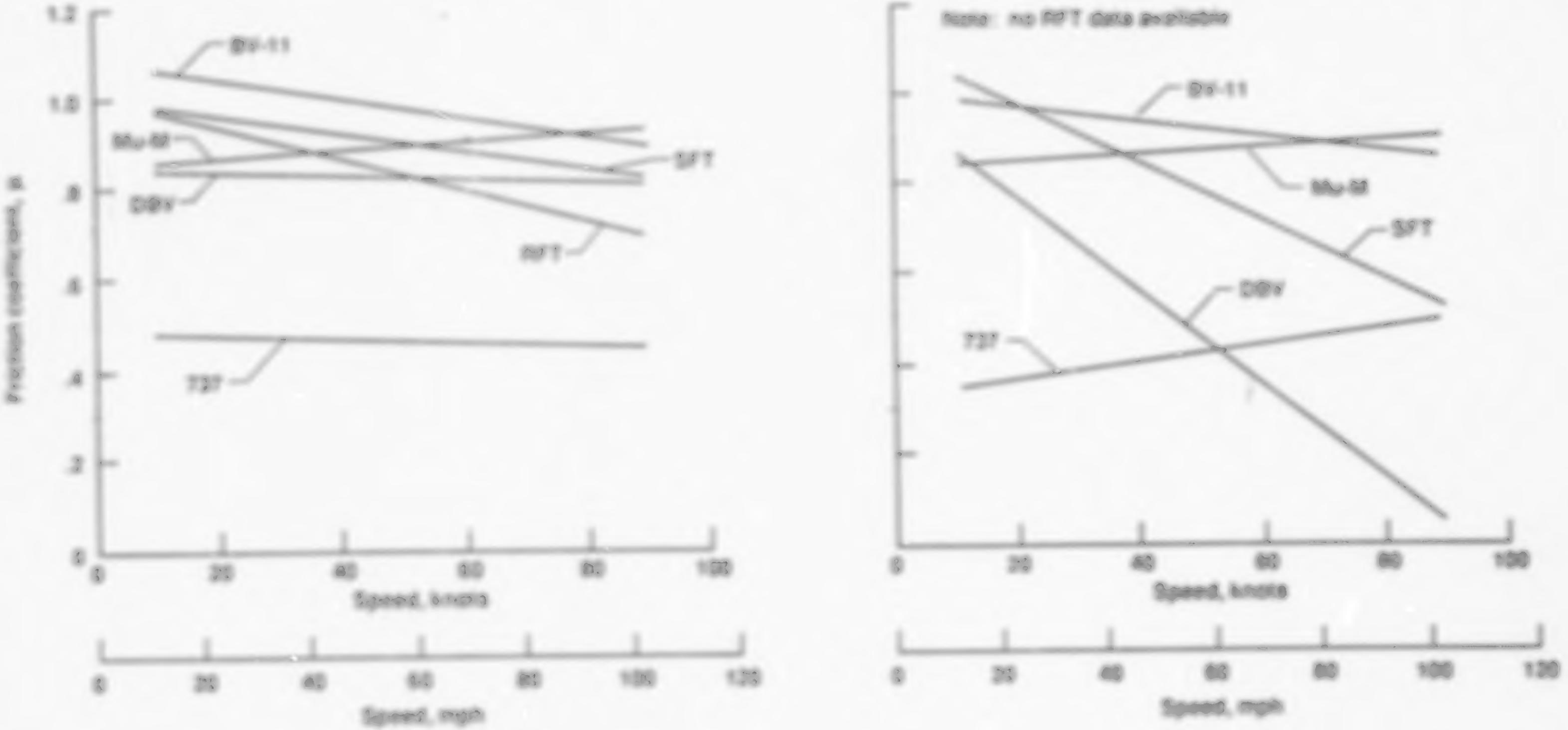


Figure 3.13 Ground Vehicle Friction Correlation Chart

Source: Ref. 47, Fig. 2

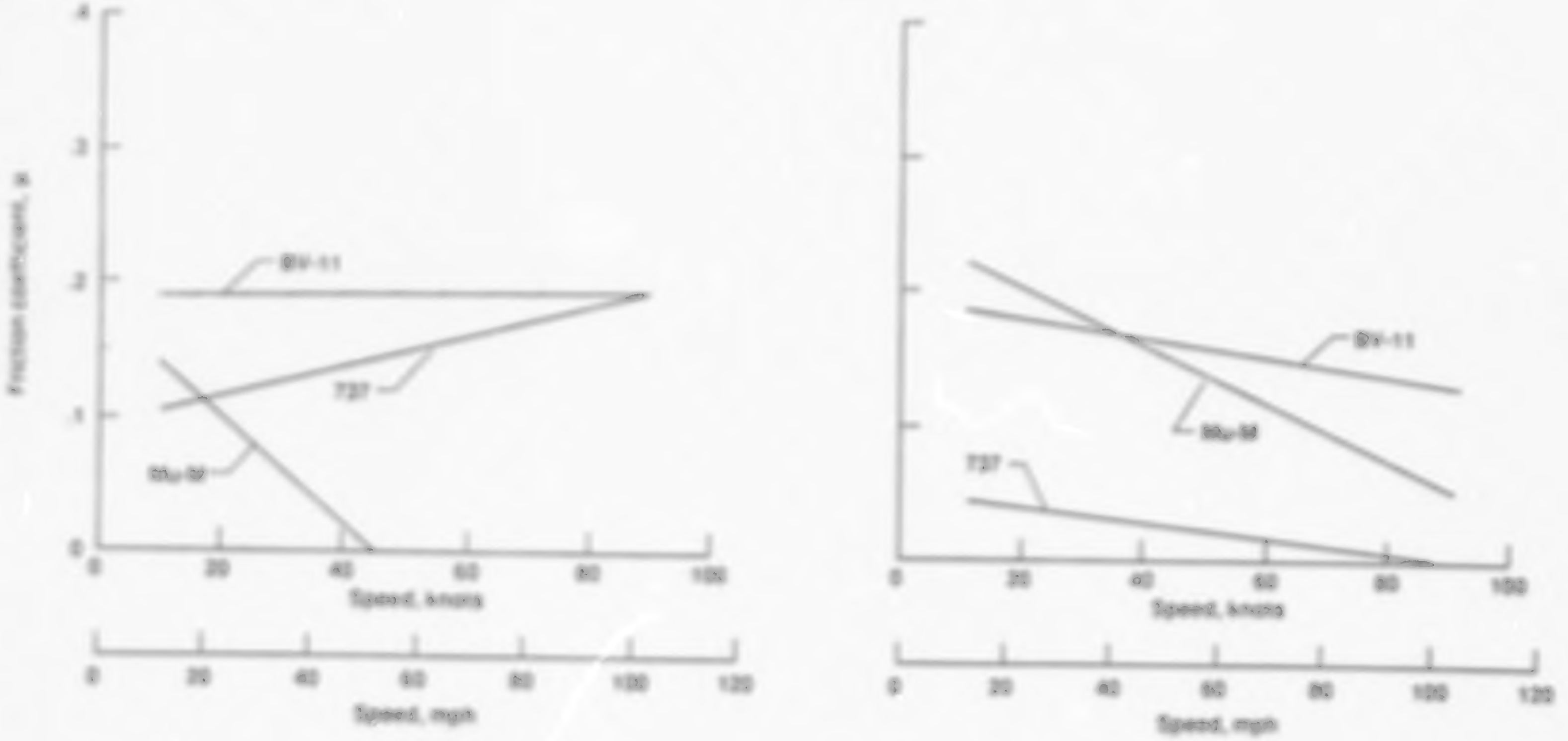


(a) Dry, all surfaces.

(b) Rain wet, SSA.

Figure 3.14 Range of Boeing 737 Aircraft and Ground-vehicle Friction Data for Different Runway Test-surface Conditions

Source: Ref. 56, Fig. 49, Pages 239-240

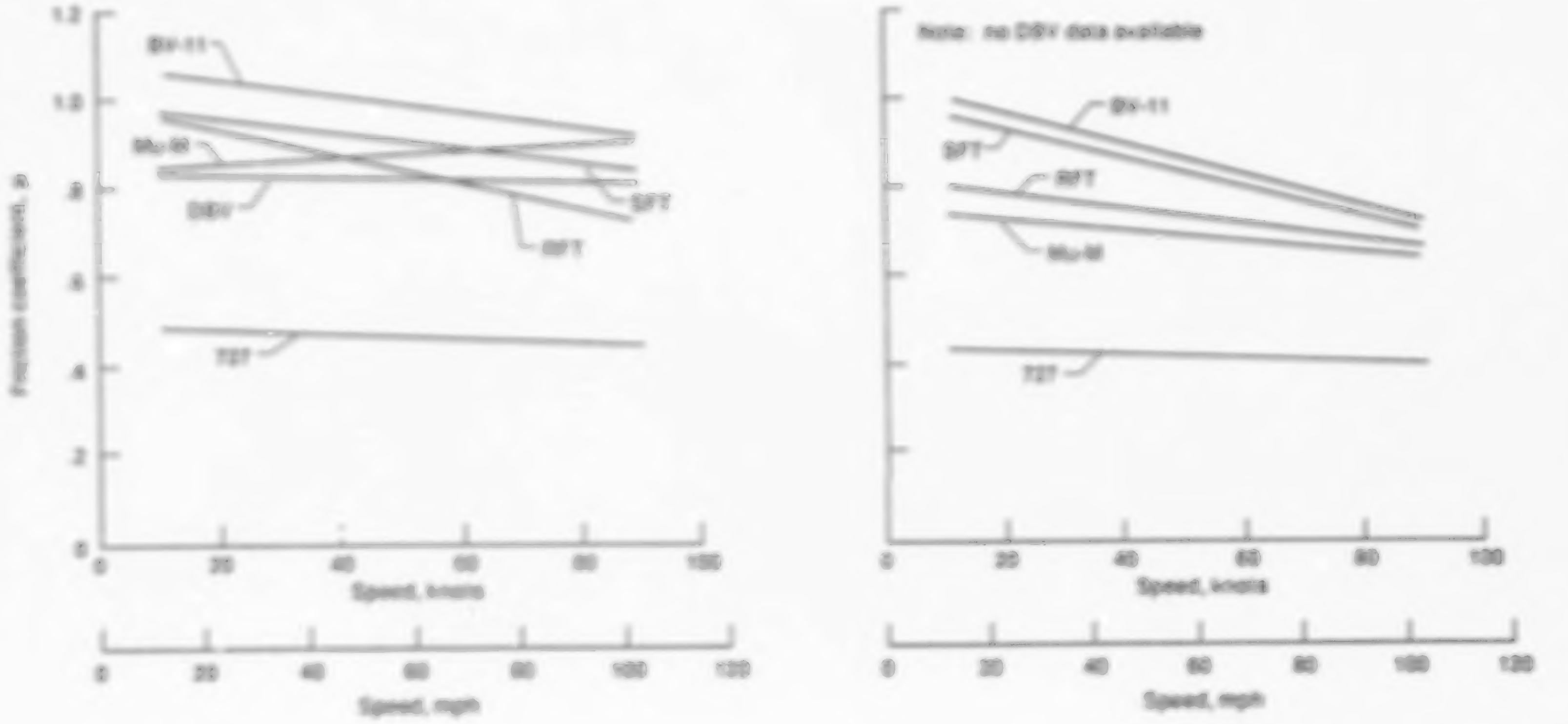


(e) 1.5-in. new wet snow

(f) Glare ice.

Figure 3.14 Range of Boeing 737 Aircraft and Ground-vehicle Friction Data for Different Runway Test-surface Conditions (Continued)

Source: Ref. 56, Fig. 49, Pages 239-240

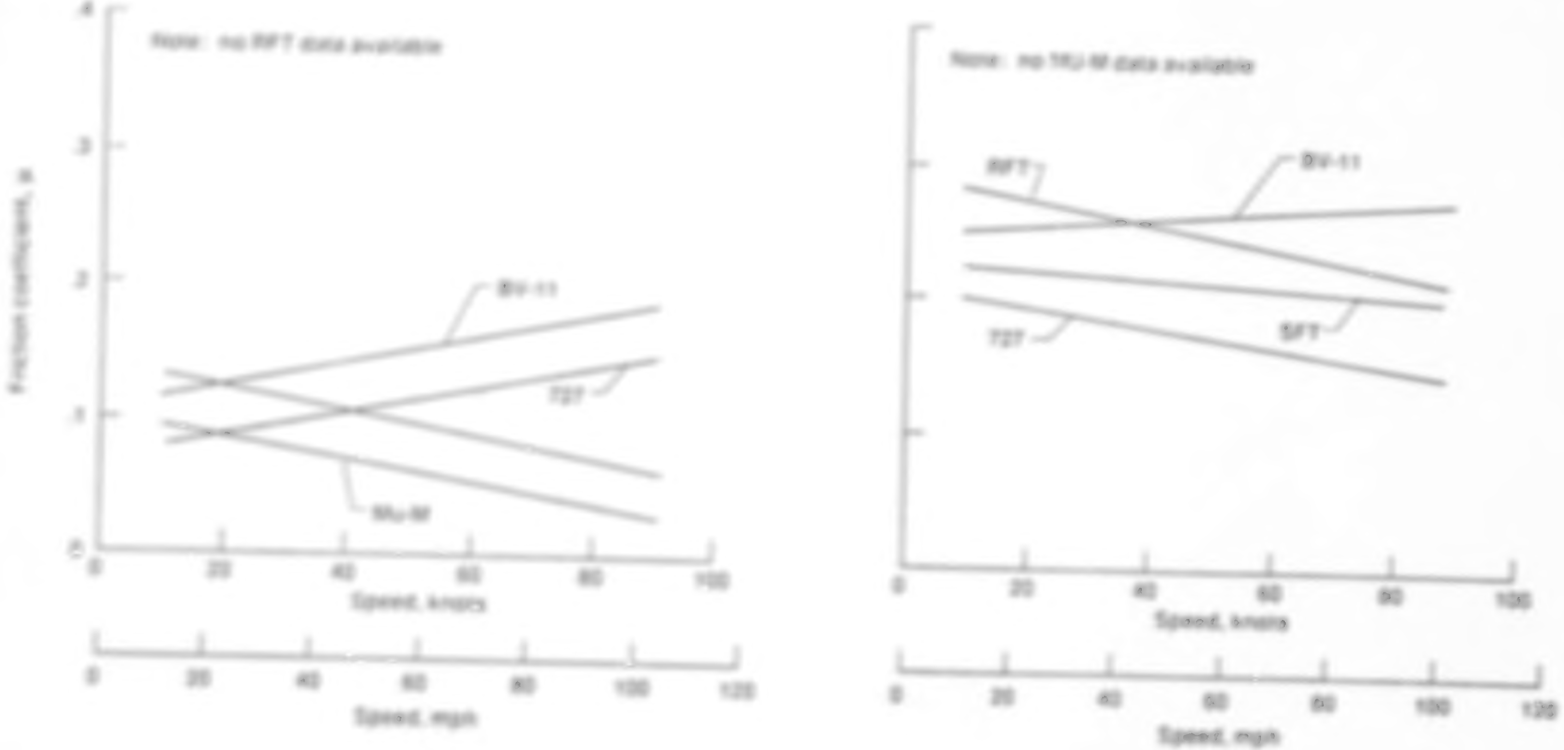


(a) Dry, all surfaces.

(b) Rain-damp, PFC surface at Pease AFB; Rain rate = 0.01 in/hr; Water depth < 0.01 in.

Figure 3.15 Range of Boeing 727 Aircraft and Ground-vehicle Friction Data for Different Runway Test-surface Conditions

Source: Ref. 54, Fig. 58, Pages 261-262

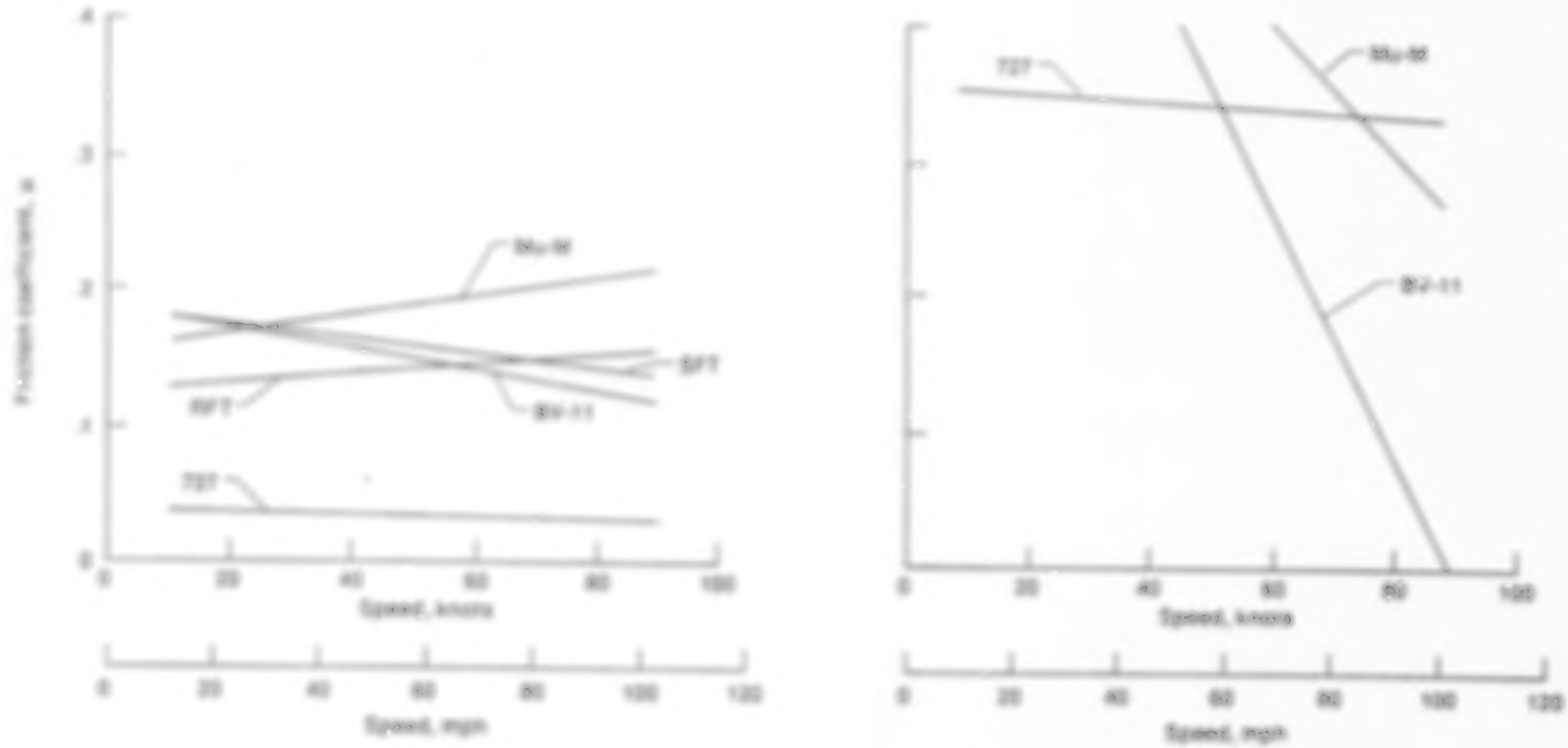


(j) Loose dry snow.

(k) UCAR on ice.

Figure 3.15 Range of Boeing 727 Aircraft and Ground-vehicle Friction Data for Different Runway Test-surface Conditions (Continued)

Source: Ref. 56, Fig. 50, Pages 261-262



(l) Solid ice.

(m) 0.25-in. slush.

Figure 3.15 Range of Boeing 727 Aircraft and Ground-vehicle Friction Data for Different Runway Test-surface Conditions (Continued)

Source: Ref. 56, Fig. 58, Pages 261-262

snow, and ice conditions. The results were reported in Ref. 13 and were supportive of a diagonal braked vehicle (DBV) as a means to measure stopping distance on slippery wet surfaces and to permit accurate prediction of the stopping distance of an aeroplane under varied runway conditions and a realistic means for calculation of crosswind limitations.

It also concluded that the JBI decelerometer which provides a runway condition reading (RCR) can considerably underestimate the actual aeroplane landing distance on a wet runway. A similar finding is made by NASA (Ref. 56) because the RCR vehicle wheel lockup becomes inconsistent under wet conditions and vehicle stability is degraded.

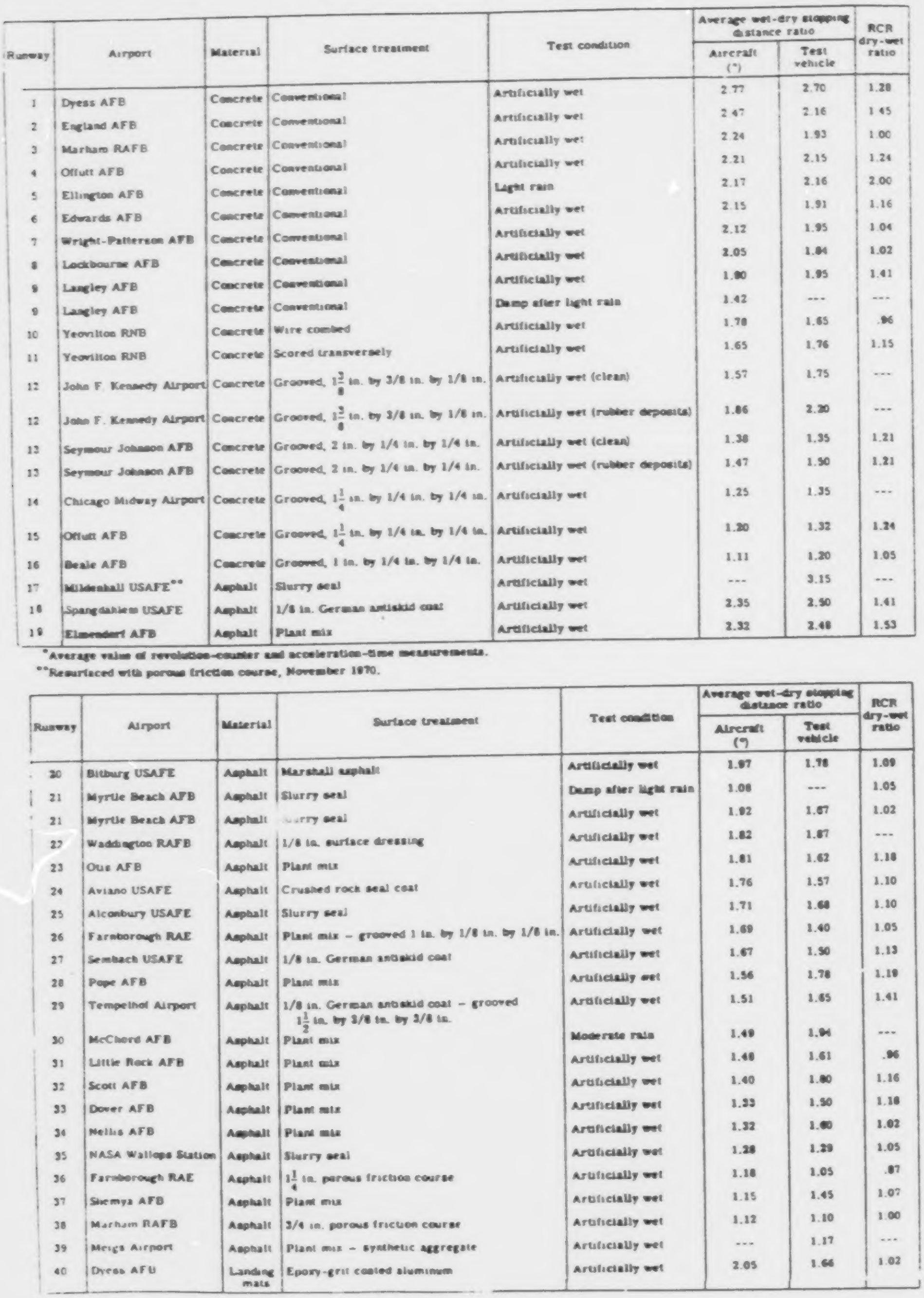
In fact Table 3.2 (from Ref. 13) illustrates good comparison of wet/dry stopping distance ratio for 50 different runways with the C141A and the DBV equipment, whereas the ratios for the RCR (based on the JBI) are noticeably different. Table 3.2 offers a further similarity to the 1990 NASA data (Ref. 56) because the dry/ice ratio for dry or packed snow on ice is approximately (3.564) to 1 compared with the 1990 ratio of 4 to 1.

The two reports are generally supportive of the results on dry runways in that no influences were found other than pavement surface condition and contaminants such as dust, oil film, rubber deposits, and tire condition.

3.4.3 Summary of Test Equipment Correlation

This review of the international data on runway friction test equipment indicates that variable correlation exists in the data and that a good understanding of the influences of variables upon the correlation integrity is essential to dealing with the correlation of measurements by ground test vehicles to the aeroplane braking characteristics on contaminated runways. The use of the most appropriate tire for each test vehicle is essential and appears to be well understood by the testing organizations, even to the extent of adopting an aero type tire with 100 psi pressure and grooves for winter test conditions on the BV11 Skiddometer.

Table 3.2 Summary of Wet-dry Stopping Distance Ratio



Runway	Airport	Material	Surface treatment	Test condition	Average wet-dry stopping distance ratio		RCR dry-wet ratio
					Aircraft (*)	Test vehicle	
1	Dyess AFB	Concrete	Conventional	Artificially wet	2.77	2.70	1.28
2	England AFB	Concrete	Conventional	Artificially wet	2.47	2.16	1.45
3	Marham RAFB	Concrete	Conventional	Artificially wet	2.24	1.93	1.00
4	Offutt AFB	Concrete	Conventional	Artificially wet	2.21	2.15	1.24
5	Ellington AFB	Concrete	Conventional	Light rain	2.17	2.16	2.00
6	Edwards AFB	Concrete	Conventional	Artificially wet	2.15	1.91	1.16
7	Wright-Patterson AFB	Concrete	Conventional	Artificially wet	2.12	1.95	1.04
8	Lockbourne AFB	Concrete	Conventional	Artificially wet	2.05	1.84	1.02
9	Langley AFB	Concrete	Conventional	Artificially wet	1.80	1.95	1.41
9	Langley AFB	Concrete	Conventional	Damp after light rain	1.42	---	---
10	Yeovilton RNB	Concrete	Wire combed	Artificially wet	1.78	1.65	.96
11	Yeovilton RNB	Concrete	Scored transversely	Artificially wet	1.65	1.76	1.15
12	John F. Kennedy Airport	Concrete	Grooved, $1\frac{3}{8}$ in. by 3/8 in. by 1/8 in.	Artificially wet (clean)	1.57	1.75	---
12	John F. Kennedy Airport	Concrete	Grooved, $1\frac{3}{8}$ in. by 3/8 in. by 1/8 in.	Artificially wet (rubber deposits)	1.86	2.20	---
13	Seymour Johnson AFB	Concrete	Grooved, 2 in. by 1/4 in. by 1/4 in.	Artificially wet (clean)	1.38	1.35	1.21
13	Seymour Johnson AFB	Concrete	Grooved, 2 in. by 1/4 in. by 1/4 in.	Artificially wet (rubber deposits)	1.47	1.50	1.21
14	Chicago Midway Airport	Concrete	Grooved, $1\frac{1}{4}$ in. by 1/4 in. by 1/4 in.	Artificially wet	1.25	1.35	---
15	Offutt AFB	Concrete	Grooved, $1\frac{1}{4}$ in. by 1/4 in. by 1/4 in.	Artificially wet	1.20	1.32	1.24
16	Beale AFB	Concrete	Grooved, 1 in. by 1/4 in. by 1/4 in.	Artificially wet	1.11	1.20	1.05
17	Mildenhall USAFE**	Asphalt	Slurry seal	Artificially wet	---	3.15	---
18	Spangdahlem USAFE	Asphalt	1/8 in. German antiskid coat	Artificially wet	2.35	2.50	1.41
19	Elmendorf AFB	Asphalt	Plant mix	Artificially wet	2.32	2.48	1.53
20	Bitburg USAFE	Asphalt	Marshall asphalt	Artificially wet	1.97	1.78	1.09
21	Myrtle Beach AFB	Asphalt	Slurry seal	Damp after light rain	1.08	---	1.05
21	Myrtle Beach AFB	Asphalt	Slurry seal	Artificially wet	1.92	1.87	1.02
22	Waddington RAFB	Asphalt	1/8 in. surface dressing	Artificially wet	1.82	1.87	---
23	Otis AFB	Asphalt	Plant mix	Artificially wet	1.81	1.62	1.18
24	Aviano USAFE	Asphalt	Crushed rock seal coat	Artificially wet	1.76	1.57	1.10
25	Alconbury USAFE	Asphalt	Slurry seal	Artificially wet	1.71	1.68	1.10
26	Farnborough RAE	Asphalt	Plant mix – grooved 1 in. by 1/8 in. by 1/8 in.	Artificially wet	1.69	1.40	1.05
27	Sembach USAFE	Asphalt	1/8 in. German antiskid coat	Artificially wet	1.67	1.50	1.13
28	Pope AFB	Asphalt	Plant mix	Artificially wet	1.56	1.78	1.19
29	Tempelhof Airport	Asphalt	1/8 in. German antiskid coat – grooved $1\frac{1}{2}$ in. by 3/8 in. by 3/8 in.	Artificially wet	1.51	1.65	1.41
30	McChord AFB	Asphalt	Plant mix	Moderate rain	1.49	1.94	---
31	Little Rock AFB	Asphalt	Plant mix	Artificially wet	1.48	1.61	.96
32	Scott AFB	Asphalt	Plant mix	Artificially wet	1.40	1.80	1.16
33	Dover AFB	Asphalt	Plant mix	Artificially wet	1.33	1.50	1.18
34	Nellis AFB	Asphalt	Plant mix	Artificially wet	1.32	1.60	1.02
35	NASA Wallops Station	Asphalt	Slurry seal	Artificially wet	1.28	1.29	1.05
36	Farnborough RAE	Asphalt	$1\frac{1}{4}$ in. porous friction course	Artificially wet	1.18	1.05	.87
37	Shemya AFB	Asphalt	Plant mix	Artificially wet	1.15	1.45	1.07
38	Marham RAFB	Asphalt	3/4 in. porous friction course	Artificially wet	1.12	1.10	1.00
39	Meigs Airport	Asphalt	Plant mix – synthetic aggregate	Artificially wet	---	1.17	---
40	Dyess AFB	Landing mats	Epoxy-grit coated aluminum	Artificially wet	2.05	1.66	1.02

*Average value of revolution-counter and acceleration-time measurements.

**Resurfaced with porous friction course, November 1970.

Source: Ref. 13, Table II

Table 3.2 Summary of Wet-dry Stopping Distance Ratio (Continued)

Runway	Airport	Material	Surface treatment	Test condition		Average wet-dry stopping distance ratio		RCR dry-wet ratio
				Temperature, °F	Surface cover	Aircraft (*)	Test vehicle	
41	Malmstrom AFB	Concrete (ramp)	Conventional	27	Packed dry snow	3.71	4.16	6.00
42	Loring AFB	Asphalt	Slurry seal	21	Glazed ice and dry snow	3.51	3.40	4.00
43	Wurtsmith AFB	Concrete	Conventional	23	Packed snow and ice	3.31	3.65	12.00
44	Grissom AFB	Asphalt (taxiway)	Plant mix	22	Packed snow and ice	3.20	3.95	4.80
45	Wright-Patterson AFB	Concrete	Conventional	8	Dry packed snow and ice	2.82	2.90	4.36
46	Glenview NAS	Concrete and asphalt	Conventional	27	Patchy ice and snow	2.39	2.51	----
47	K. I. Sawyer AFB	Asphalt	Slurry seal	11	Patchy packed snow and ice	2.27	1.63	----
47	K. I. Sawyer AFB	Asphalt	Slurry seal	23	Packed snow and ice	2.25	2.27	3.20
48	McGuire AFB	Asphalt	Plant mix	14	Patchy snow and ice	1.84	2.17	2.53
49	Malmstrom AFB	Asphalt (runway)	Plant mix	33	Patchy slush	1.75	1.62	1.72

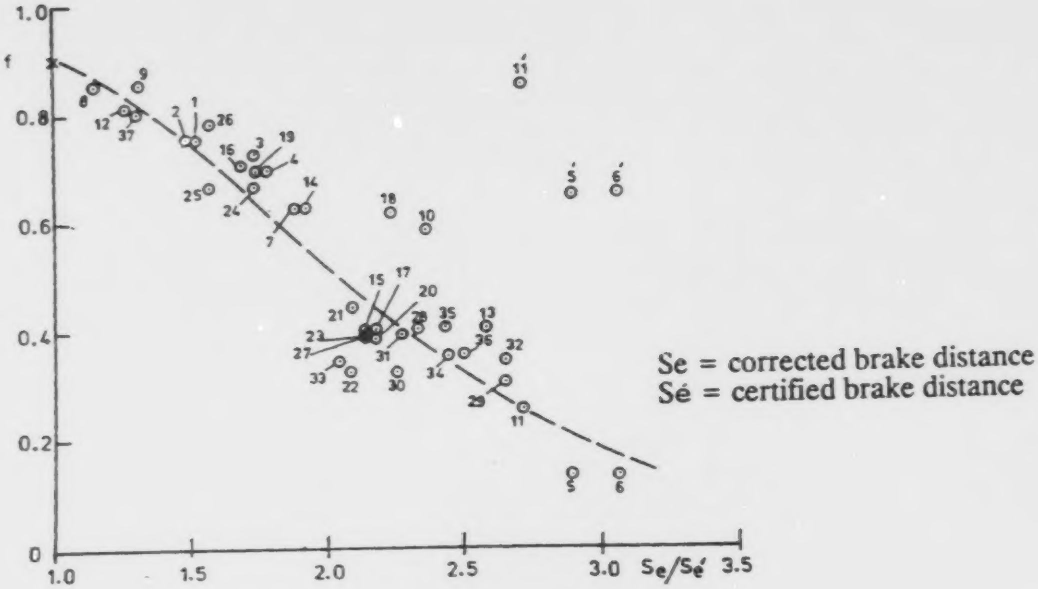
*Average value of revolution-counter and acceleration-time measurements.

Source: Ref. 13, Table II

Other refinements in testing for optimum correlation include variations in speed, water depth, surface type and texture, tire tread design, inflation pressure, solar testing, type of chemical deicing treatment, proper vehicle maintenance, regular calibration checks of instruments, operator proficiency, random water ponding, wind patterns and rainfall rates.

Figures 3.16 to 3.21 illustrate degrees of correlation between ground test measurements and aeroplane effective friction.

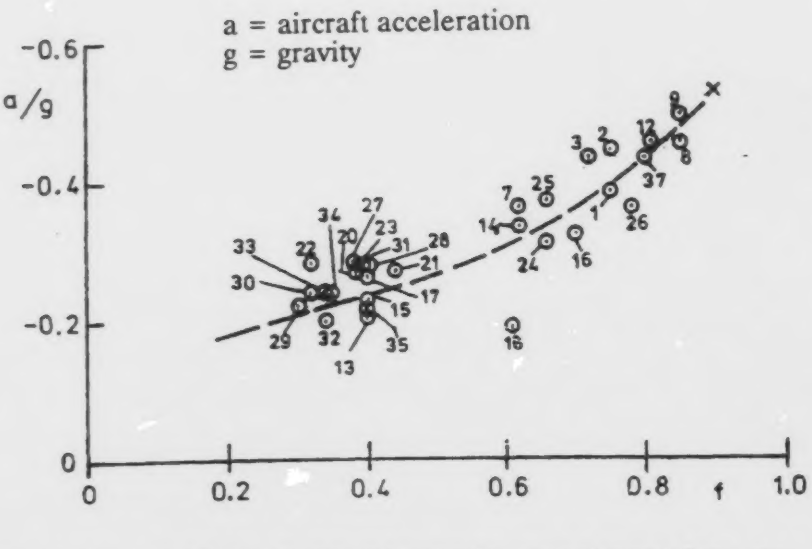
Most test agencies have reported correlation or lack of it between types of test vehicles and aeroplanes under specific conditions, but mostly in absolute terms which compares friction indices for each type of equipment and the aeroplanes, such as in Figure 3.11. As a consequence it is advisable when comparing data to study the test conditions to ascertain whether direct comparisons are valid. This is not unreasonable for test data but is not suitable or acceptable for routine operations where the test data from runway friction test equipment is intended to be utilized for determining all aeroplane effective friction.



Se = corrected brake distance
Sé = certified brake distance

Figure 3.16 Brake Numbers, f, Measured with BV-11 (Low Pressure Tire) vs. Relative Brake Distance of Fokker F-28

Source: Ref. 50, Fig. 14



a = aircraft acceleration
g = gravity

Figure 3.17 Fokker F-28 Aircraft Deceleration vs. BV-11 Measured Brake Numbers, f

Source: Ref. 50, Fig. 15

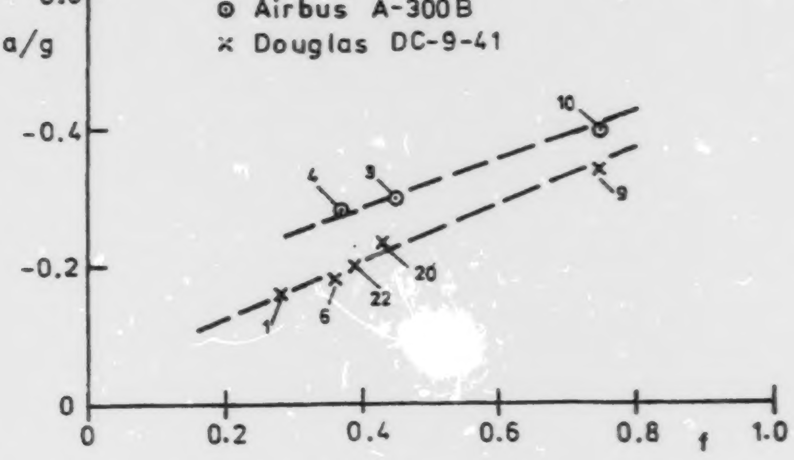


Figure 3.18 Aircraft Deceleration vs. Friction Tester (High Pressure Tire) Measured Brake Numbers, f

Source: Ref. 50, Fig. 14

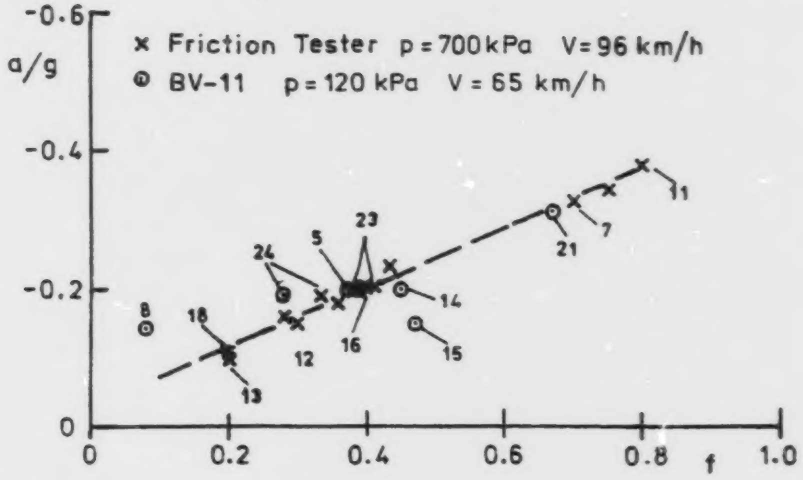


Figure 3.19 Aircraft DC-9-41 Deceleration vs. Vehicle Measured Brake Numbers, f

Source: Ref. 50, Fig. 21

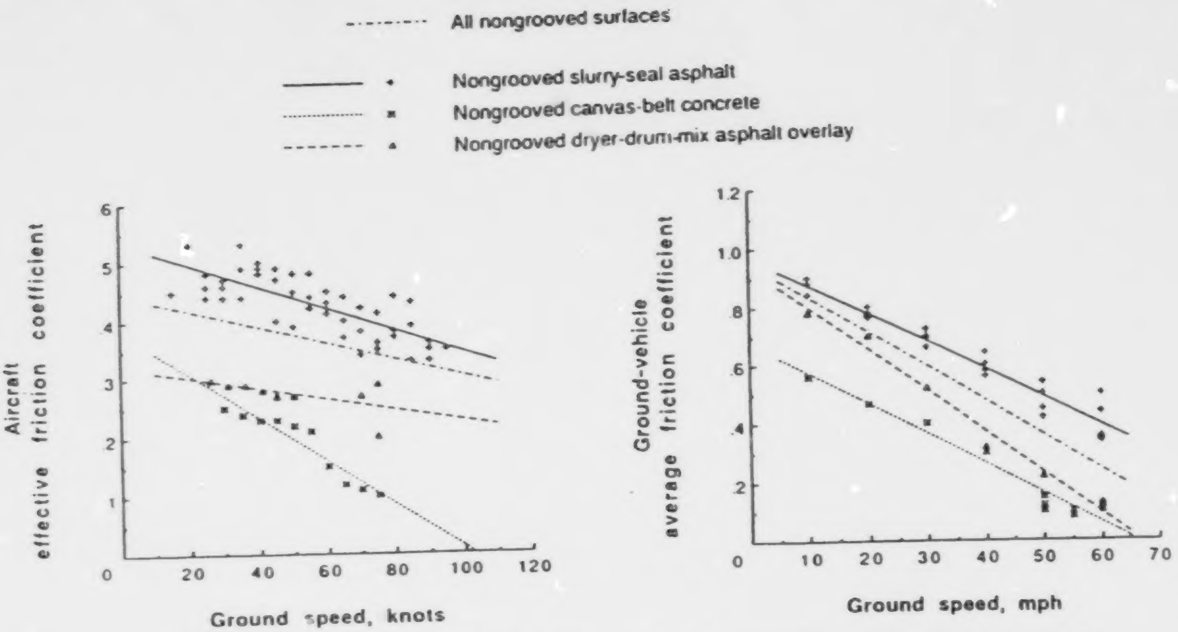


Figure 3.20 Variation of Boeing 727 Aircraft and DBV Ground-Vehicle Friction Data With Speed on Truck-wet, Nongrooved Test Surfaces

Source: Ref. 56, Fig. 59, Page 268

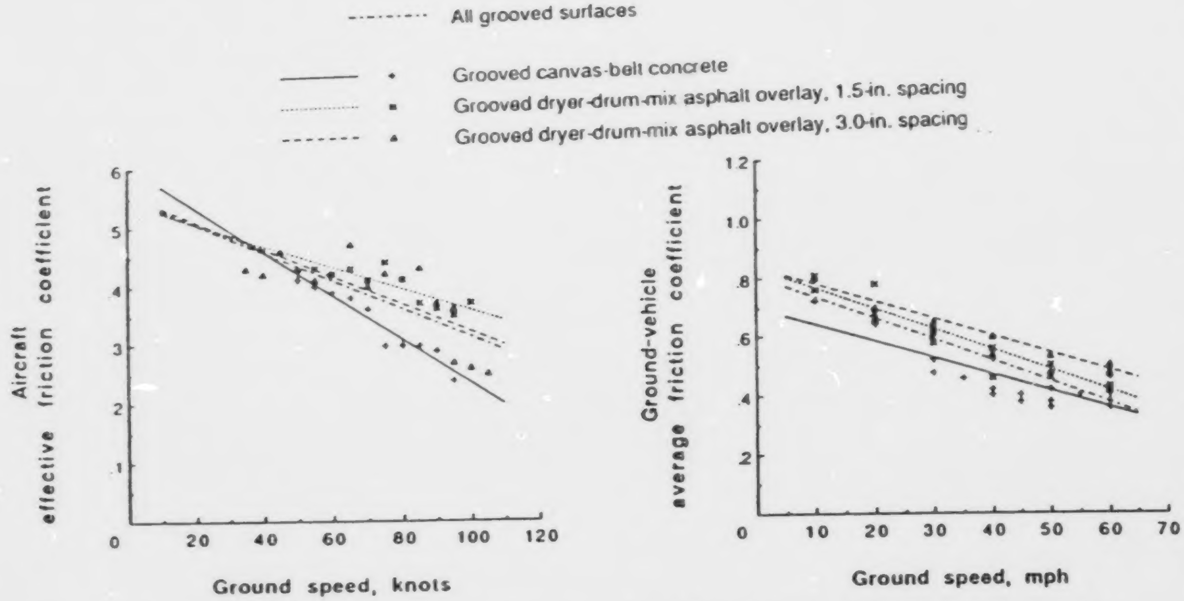


Figure 3.21 Variation of Boeing 727 Aircraft and DBV, Ground-Vehicle Friction on Data with Speed on Truck-wet, Grooved Test Surfaces

Source: Ref. 56, Fig. 60, Page 273

Thus the applicability of runway friction test equipment results to aeroplane braking friction, cross-wind controllability and predicted stopping distances is, not surprisingly, inconsistent from airport to airport, country to country, and not sufficiently reliable to engender confidence in a quantitative methodology either in the aeroplane flight manual or as supplemental information to take-off and landing performance in all weather conditions.

However, this is not to negate the test data or the national practices of countries which have adapted the ICAO SARPS for runway friction testing and reporting to operators (pilots). Sweden, Japan, and the European JAR countries have made good progress, and the FAA is expected to support some of these practices in the new addition of AC 91-6B in 1991. In fact, the most recent USA test data in Ref. 56 includes methods for predicting the aeroplane friction from the ground tests. Examples of the accuracy of this prediction are given in Figure 3.22.

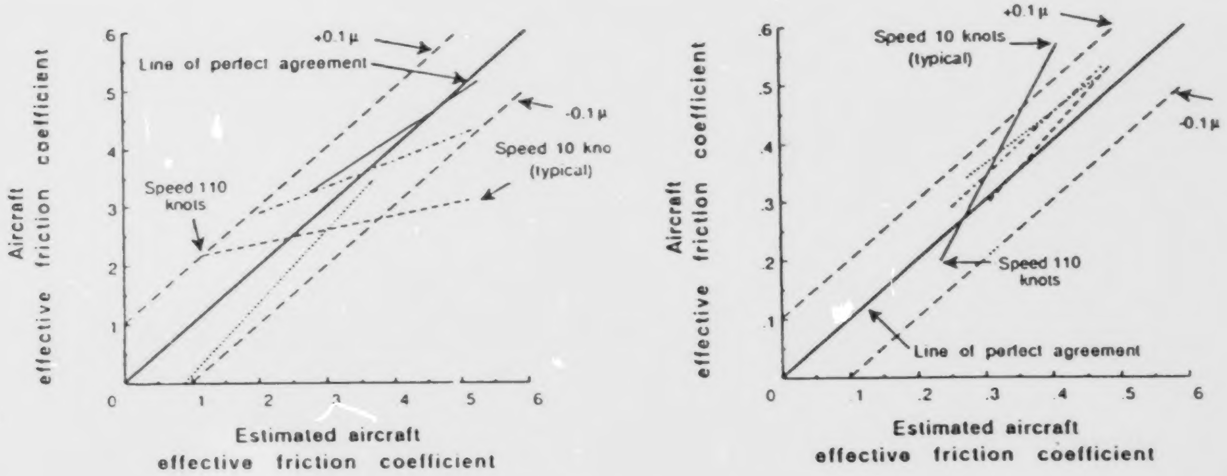


Figure 3.22 Variation of Estimated μ With Actual Aircraft μ for Boeing 727 Aircraft Based on DBV Ground-vehicle Friction Data on Truck-wet, Grooved and Ungrooved Test Surfaces

Source: Ref. 56, from Fig. 59 and 60

Further discussion of this point will be undertaken in the Section 7 dealing with countermeasures and will deal with a parametric approach to help resolve the inadequacies of the absolute measurement concept. Also, in Section 5, dealing with the national classification of runway condition by country and by airline, the practices are reviewed and the total picture becomes clear as to the various means of providing runway condition reports to operators (pilots) and the basis upon which take-off planning is being managed qualitatively and quantitatively.

3.4.4 Measures to Improve Runway Friction

The effect of the runway surface texture is reasonably well understood by the aeronautical authorities, ICAO, the major airlines, and the aeroplane manufacturers. Modern runway construction requires that the micro and macro qualities are neither smooth nor closed since adhesion, and hysteresis friction qualities need to be protected, particularly in relation to aeroplane stopping distances during wet and contaminated conditions.

However, old runways and those whose texture has been changed due to dirt, rubber, oil and grease contaminants are usually smooth and closed or a variation of textures exists over the runway length. An airport authority or operator should inspect and restore runway texture by removing rubber and dirt. If these practices are not being followed then under wet or snow and slush conditions the prospects for acceptable runway surface conditions are poor. In some circumstances runways are resurfaced to restore an eroded surface where cracks, holes and low spots have developed which is the logical opportunity to improve the texture and friction characteristics.

Prior to discussing runway maintenance, it is worthwhile discussing grooved runways because the evidence indicates that they offer significant improvements for wet conditions. Results from the NASA Convair 880 and C141a tests, Ref. 13, demonstrated a doubling of the effective friction on wet runways with grooves compared with no grooves. Thus dynamic hydroplaning can be deterred if not prevented by runway grooves. Figures 3.35 to 3.39 from Ref. 13 are good examples of groove performance. A comprehensive discussion on groove performance is provided in Section 3.6.

The maintenance objective of airport operators should be to restore runway friction to near-dry surface performance as soon as possible during or after the snow, slush, or ice occurs. This means a vigorous and timely snow removal activity which judiciously attempts to clear the surface and or use chemicals to treat the contaminant. Today runway ice detectors are available and when used in conjunction with weather forecasts it is possible to stay on top of the operation. Further discussion on maintenance practices is provided in Section 7. A prerequisite to improving runway friction is a frequent calibration of the runway utilizing a ground test vehicle and maintaining a statistical distribution of the measurements and a record of the runway condition during and after heavy rainfalls to detect pooling and inadequate drainage. During winter months the snow and ice characteristics should be recorded including tendencies to frost heaves and cracks.

Thus, in considering measures to improve runway friction at a site, continual updating of the knowledge about the runway characteristics is essential, as is the process of keeping the civil aviation authority and the airport operators informed of the current runway conditions.

It is clear that the variability of runway friction due to runway contamination is more reliably measurable by certain types of friction measuring devices than others. Several authors have identified the non-reliability of specific devices on wet runways or at certain ranges of speed, or with non-aero tires, to name a few deficiencies. Thus, there is a need to achieve international agreement on the optimum test devices for specific types of contamination and to also agree upon the optimum frequency of runway calibration for dry and contaminated runways.

Further, the calibration of a runway should be relative to its dry friction characteristics as demonstrated by some authors who have reported results as either a dry/contaminant ratio or the contaminant/dry ratio. Ref. 13 is a good example and a table from Ref. 13 is illustrated in Table 3-2.

The mean values of such parametric ratios for the test devices reported on in Ref. 56 were 1/2 for dry conditions, 1/4 for compact snow on ice conditions and 1/5 for ice conditions. The mean values for the ratios for the aeroplanes were generally similar except for the glare ice case where a significant difference occurred. However, the parametric concept may well be beneficial if the aeroplane braking was also calibrated by the manufacturer in conjunction with ground vehicle tests for wet, snow, and ice conditions on the types of vehicles agreed internationally to be suitable for each type of contaminant.

3.5 Tire-Runway Friction

3.5.1 Background

In addition to supporting aeroplane weight during ground operations, the aeroplane tire is required to absorb impact during landing to provide a stable take-off run, and to allow braking and steering effectiveness.

Aeroplane tires have high inflation, but a flexible structure of bias-ply construction which aids cornering and cross-wind operations. The tread grooves are circumferential, the footprint is elliptical; large vertical deflection indicates large deflection energy. The material or tread compound is based on natural rubber plus curatives, fillers, and oils, to provide resistance to abrasion, tearing, and cutting, and the elastic characteristics needed over a broad range of temperatures. It is vital to achieve the balance between the adhesion component of friction and hysteresis component of friction which together provide adequate slip on both micro and macro textured surfaces (see Sections 3.1.1 and 3.1.2).

The friction which is measured as a coefficient of friction as explained in 3.1.1 is influenced by the tire construction characteristics, inflation pressure, the bearing pressure of the footprint area which is important on wet surfaces to provide the maximum contact area. Figures 3.23 and 3.24 illustrate the effect of forward speed on tire-ground contact area in wet conditions, and the effect of runway surface texture on tire-ground coefficient of friction. Reference 72 is the source of these data.

The tire characteristics are complex and during aeroplane take-off at high speed and high weight, in a crosswind, on a runway surface with changes in its surface texture over its length due to wear, rubber and dirt contamination and possible structural imperfections, plus water and snow/ice contamination, the forces on a tire include, vertical and lateral deflections, yaw, rolling friction, braking friction. Tire wear alters the effects of these as does ambient temperature, intensity of the braking, the cooling period since last full application, and the integrity of the automatic brake system which could induce oscillatory brake input, and brake fading. All of these effect the coefficient

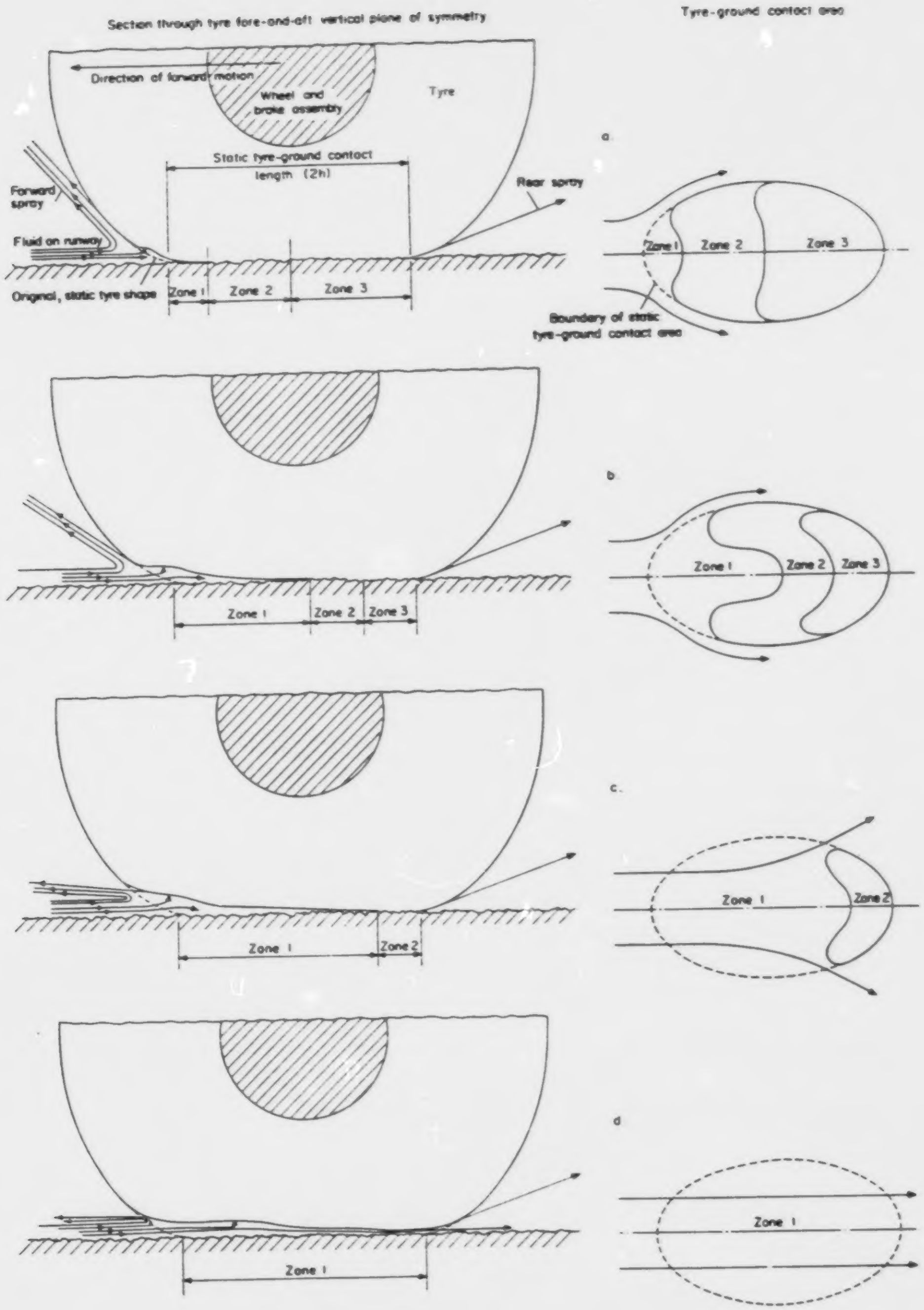
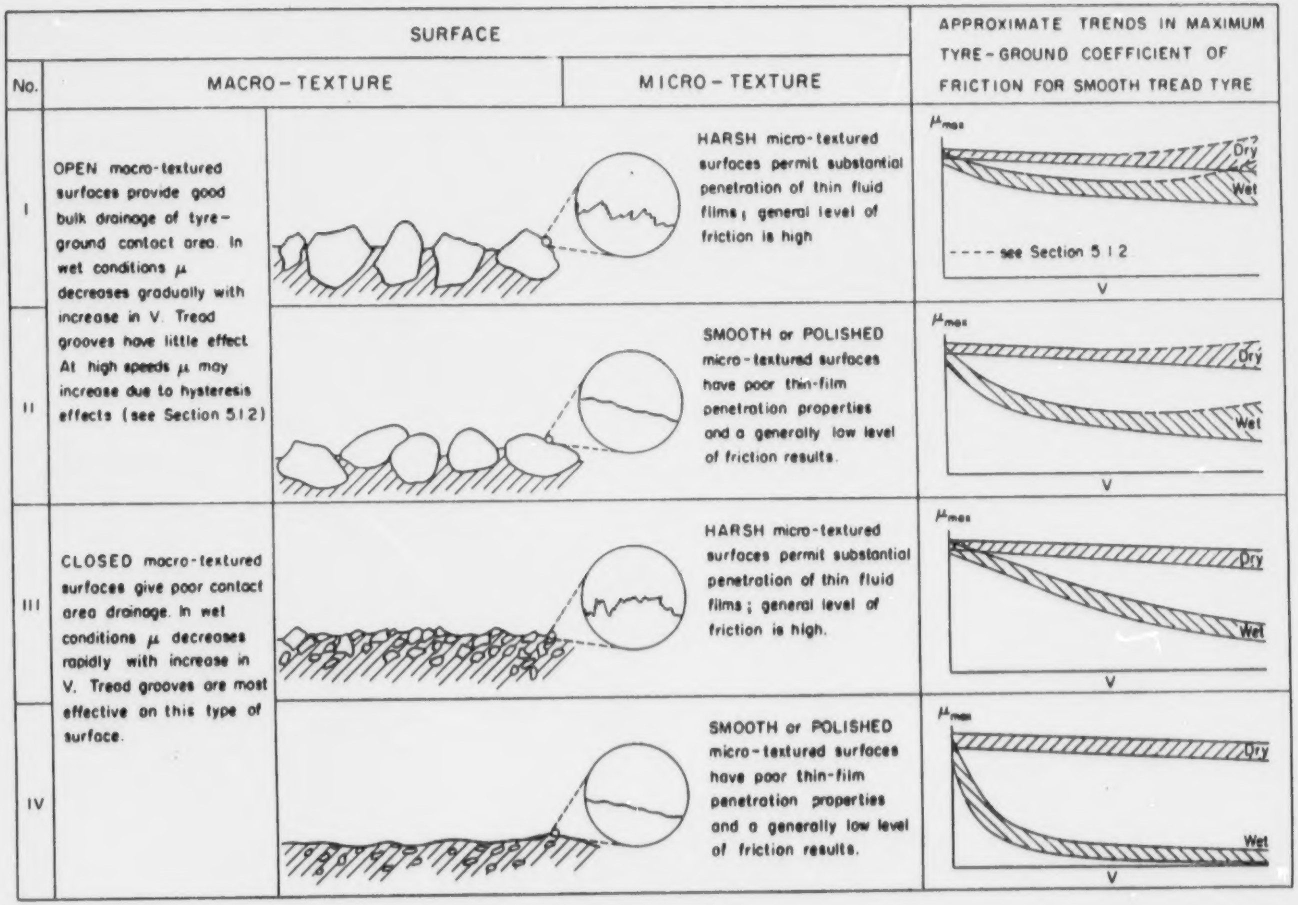

Section through tyre fore-and-aft vertical plane of symmetry
Tyre-ground contact area
Direction of forward motion
Wheel and brake assembly
Tyre
Static tyre-ground contact length (2h)
Forward spray
Rear spray
Fluid on runway
Original, static tyre shape
Zone 1
Zone 2
Zone 3
a
Boundary of static tyre-ground contact area
b
Zone 1
Zone 2
Zone 3
c
Zone 1
Zone 2
d
Zone 1

Figure 3.23 Effect of Forward Speed on Tire-Ground Contact Area in Wet Conditions

Source: Ref. 69., Fig. 6



No.	SURFACE MACRO-TEXTURE	 MICRO-TEXTURE	APPROXIMATE TRENDS IN MAXIMUM TYRE-GROUND COEFFICIENT OF FRICTION FOR SMOOTH TREAD TYRE
I	OPEN macro-textured surfaces provide good bulk drainage of tyre-ground contact area. In wet conditions μ decreases gradually with increase in V. Tread grooves have little effect. At high speeds μ may increase due to hysteresis effects (see Section 5.1.2)	HARSH micro-textured surfaces permit substantial penetration of thin fluid films; general level of friction is high	---- see Section 5.1.2
II		SMOOTH or POLISHED micro-textured surfaces have poor thin-film penetration properties and a generally low level of friction results.	
III	CLOSED macro-textured surfaces give poor contact area drainage. In wet conditions μ decreases rapidly with increase in V. Tread grooves are most effective on this type of surface.	HARSH micro-textured surfaces permit substantial penetration of thin fluid films; general level of friction is high.	
IV		SMOOTH or POLISHED micro-textured surfaces have poor thin-film penetration properties and a generally low level of friction results.	

Figure 3.24 Effect of Surface Texture on Tyre-ground Coefficient of Friction

Source: Ref. 69, Fig. 7

of friction so it is indicative of the possible reason for the difficulties in achieving correlations between aeroplane braking effectiveness and runway friction measurements by ground machines. When tire tread wear exceeds fifty percent its reliability under extreme demand is questionable.

Tire friction on wet surfaces is dictated by the fluid depths, tread depth, tire grooves and pressure, runway surface texture and whether or not the runway surface is grooved. Figures 3.25 to 3.34 are from Reference 72 and are provided to illustrate the combined effects of the tire characteristics, water contamination, and velocity on the coefficient of friction. The Figure 3.26 illustrates the μ dry of the JAR 25.1591. Figure 3.35 from Ref. 13 illustrates the effect of tread grooves.

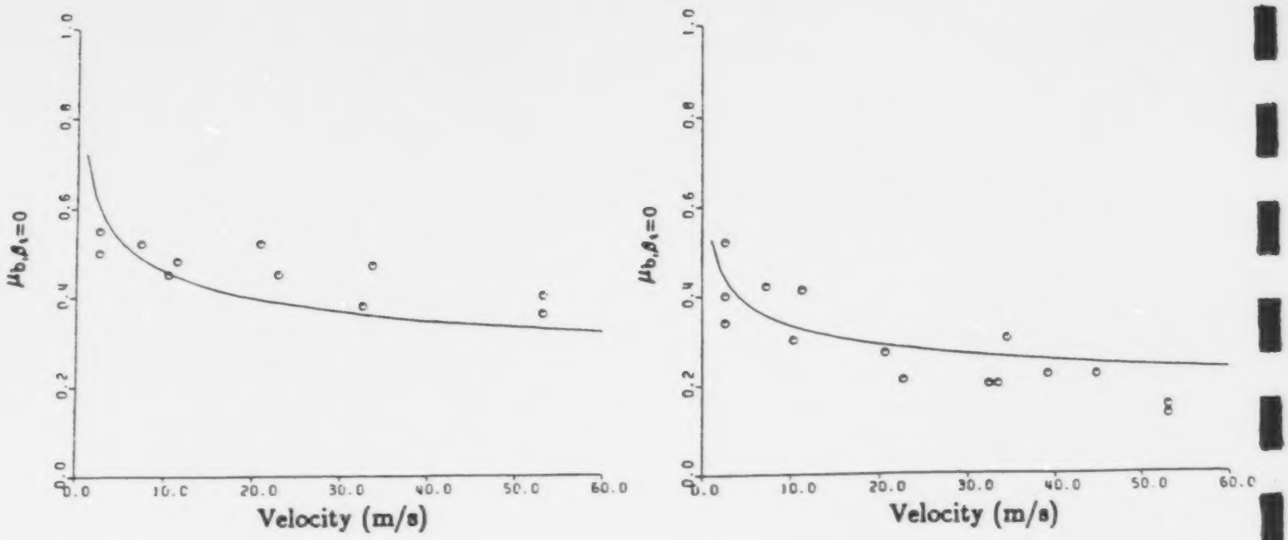
3.6 Runway Grinding and Grooving

Runway grinding is intended to restore a macrotexture to an old surface and to restore a level profile by removing bumps and high sections at faulty joints. This leaves a skid resistant, corduroy-like texture and blends patches and other irregularities into a consistent homogeneous surface which drains water faster than an unground surface.

Runway grooves are intended to eliminate hydroplaning by providing an escape route for the water compressed between the tire and pavement. As well, aeroplane braking is enhanced on grooved surfaces as illustrated in Figures 3.36 to 3.39. The grooves are cut 1/4 inch wide and deep on one inch to one and one half inch centres depending on the pavement material and age. Grooved runways exist at 24 major airports in the USA, and all the major airports of the UK and Europe. Canada has grooved Toronto LBP Airport.

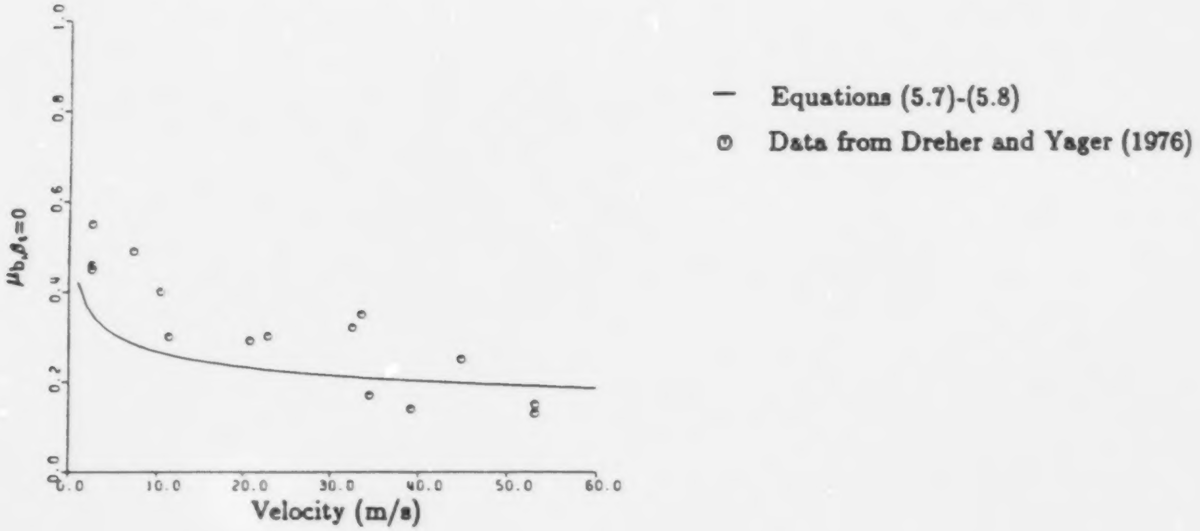
3.7 Runway Maintenance

The ICAO Airport Services Manual Doc 9137-AN/898, Part 2, Pavement Surface Conditions 1984 which is provided in Appendix A deals in detail with the requirements for maintaining runway friction characteristics, periodic assessment of conditions,



a) Dry Runway

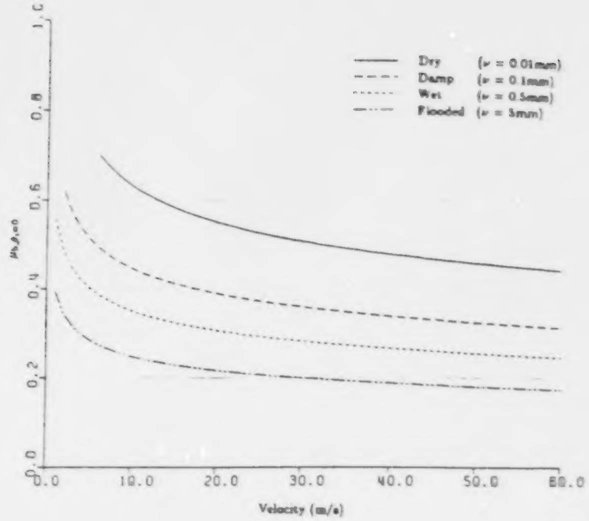
b) Wet Runway



c) Flooded Runway

Figure 3.25 Unyawed Braking Friction Coefficient vs. Velocity for a 20" X 4" Tire

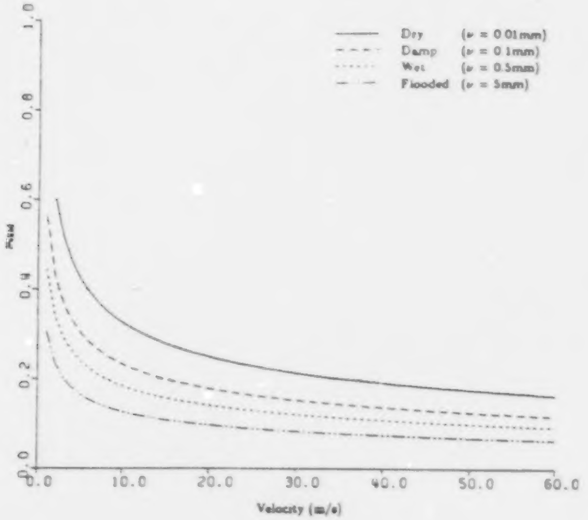
Source: Ref. 72, Fig. 5.1



(1.3x10^5 N load, rated pressure, 100μm runway texture depth)

Figure 3.26 Unyawed Braking Friction Coefficient vs. Velocity for a 46" X 16" Tire Under Various Runway Conditions

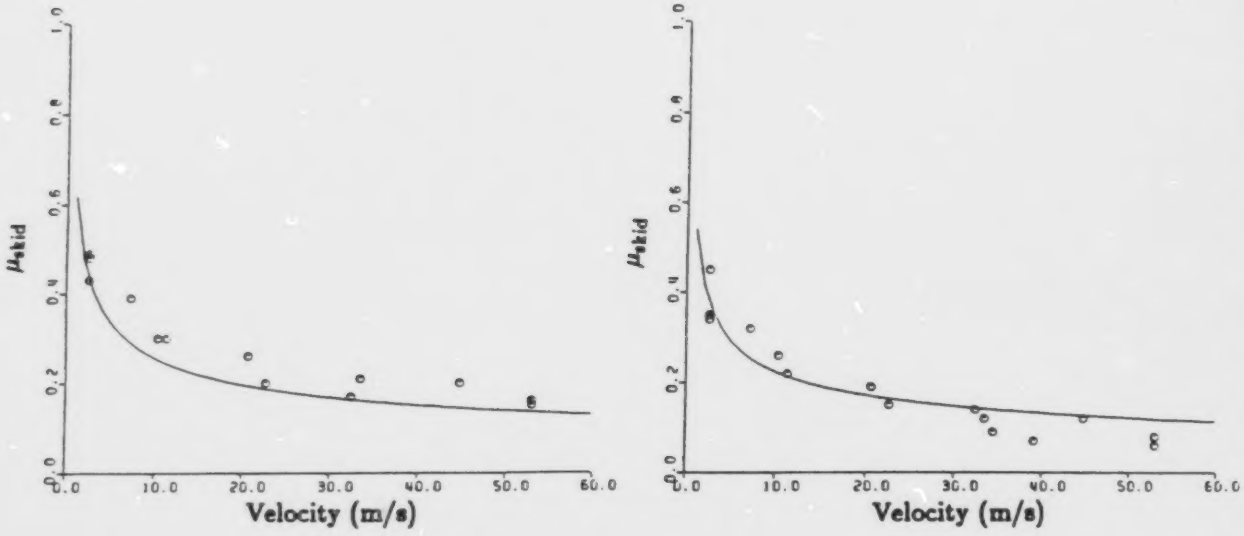
Source: Ref. 72, Fig. 5.2



(1.3x10^5 N load, rated pressure, 100μm runway texture depth)

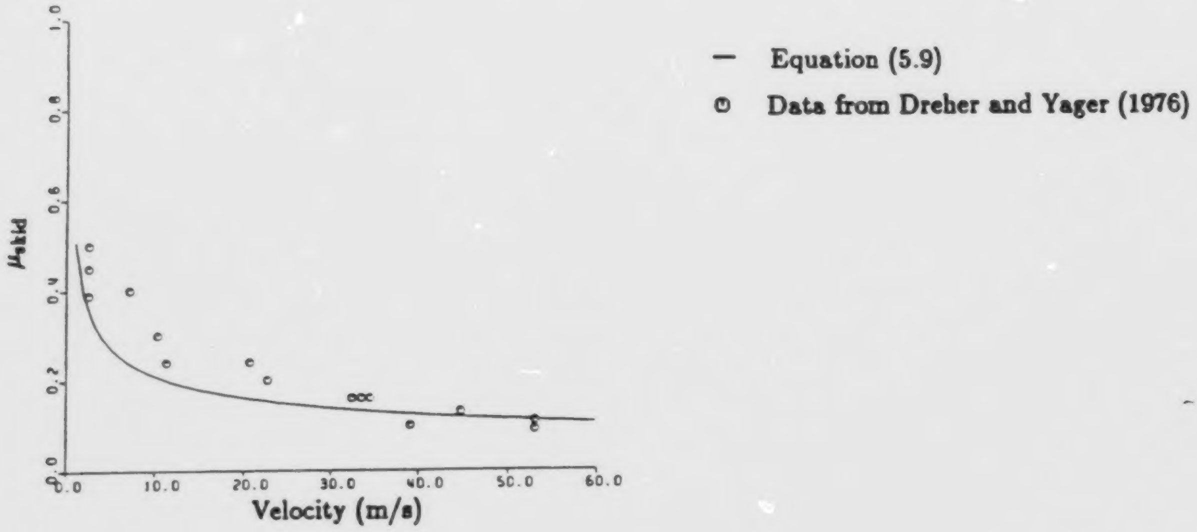
Figure 3.27 Skidding Friction Coefficient vs. Velocity for a 46" X 16" Tire Under Various Runway Conditions

Source: Ref. 72, Fig. 5.4



a) Dry Runway

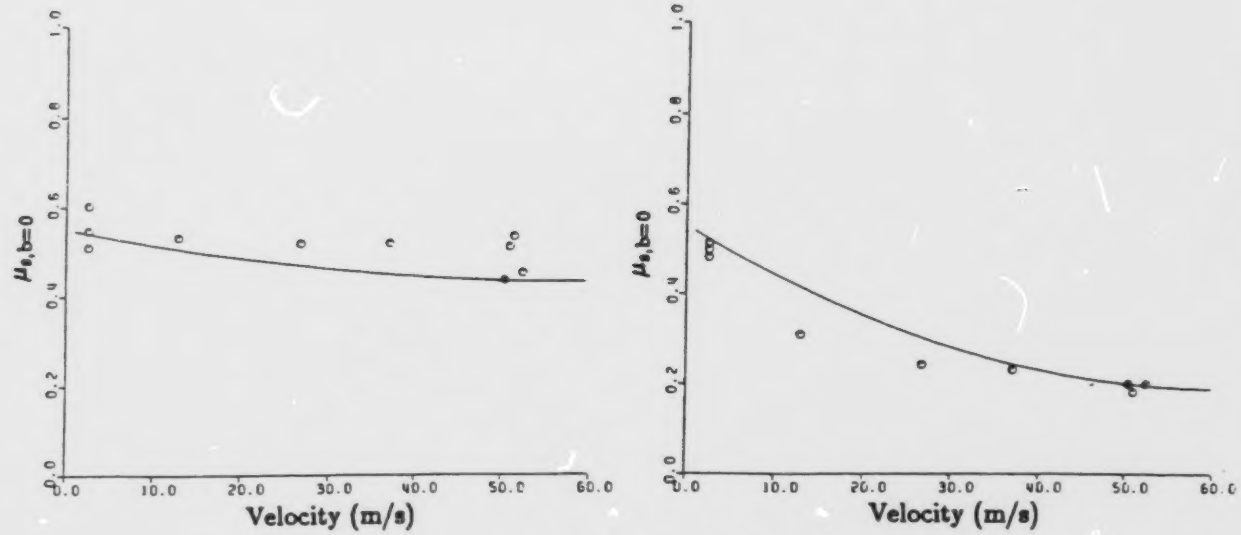
b) Wet Runway



c) Flooded Runway

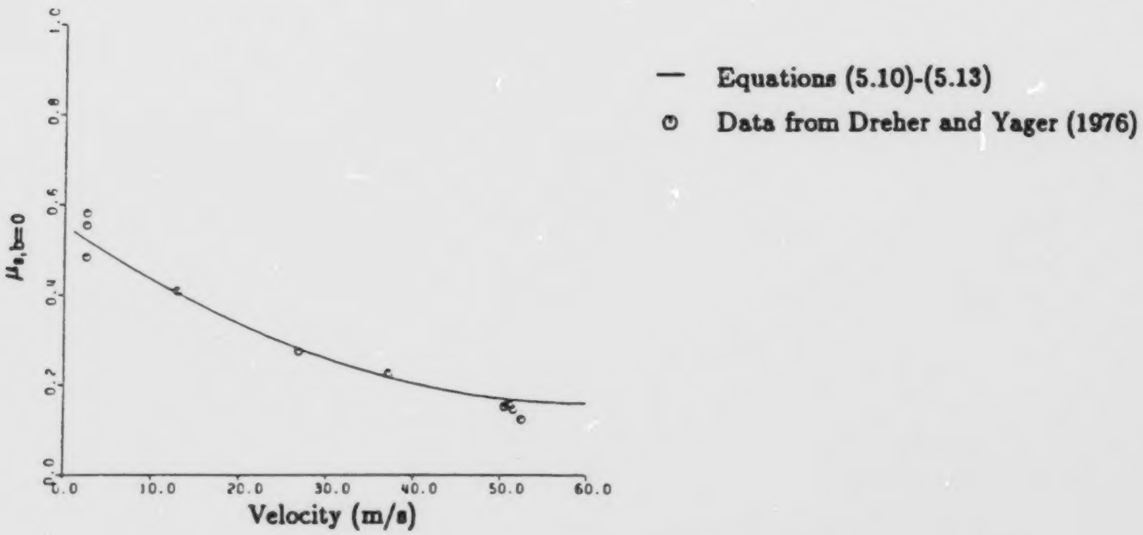
Figure 3.28 Skidding Friction Coefficient vs. Velocity for a 20" X 4" Tire

Source: Ref. 72, Fig. 5.3



a) Dry Runway

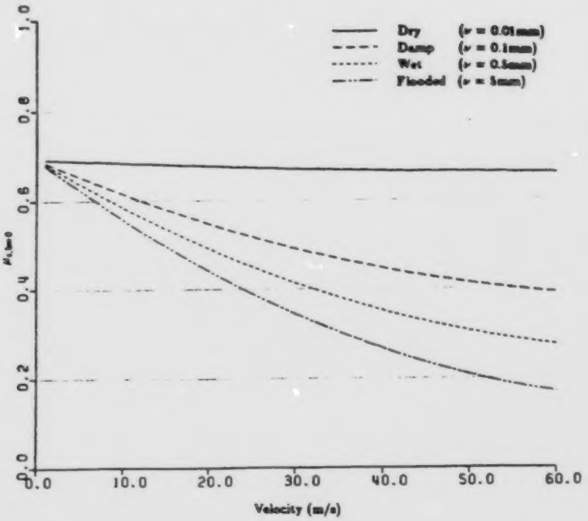
b) Wet Runway



c) Flooded Runway

Figure 3.29 Unbraked Side Friction Coefficient vs. Velocity for a 20′ X 4" Tire

Source: Ref. 72, Fig. 5.5



(1.3x10^{5} N load, rated pressure, 160μm runway texture depth)

Figure 3.30 Unbraked Side Friction Coefficient vs. Velocity for a 46" X 16" Tire Under Various Runway Conditions Using Equations (5.10)-(5.6)

Source: Ref. 72, Fig. 5.6

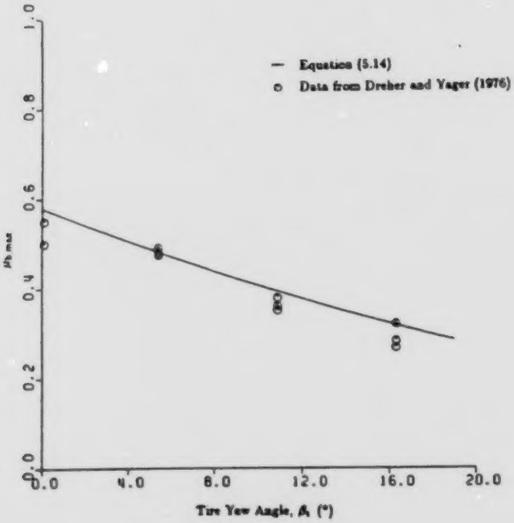
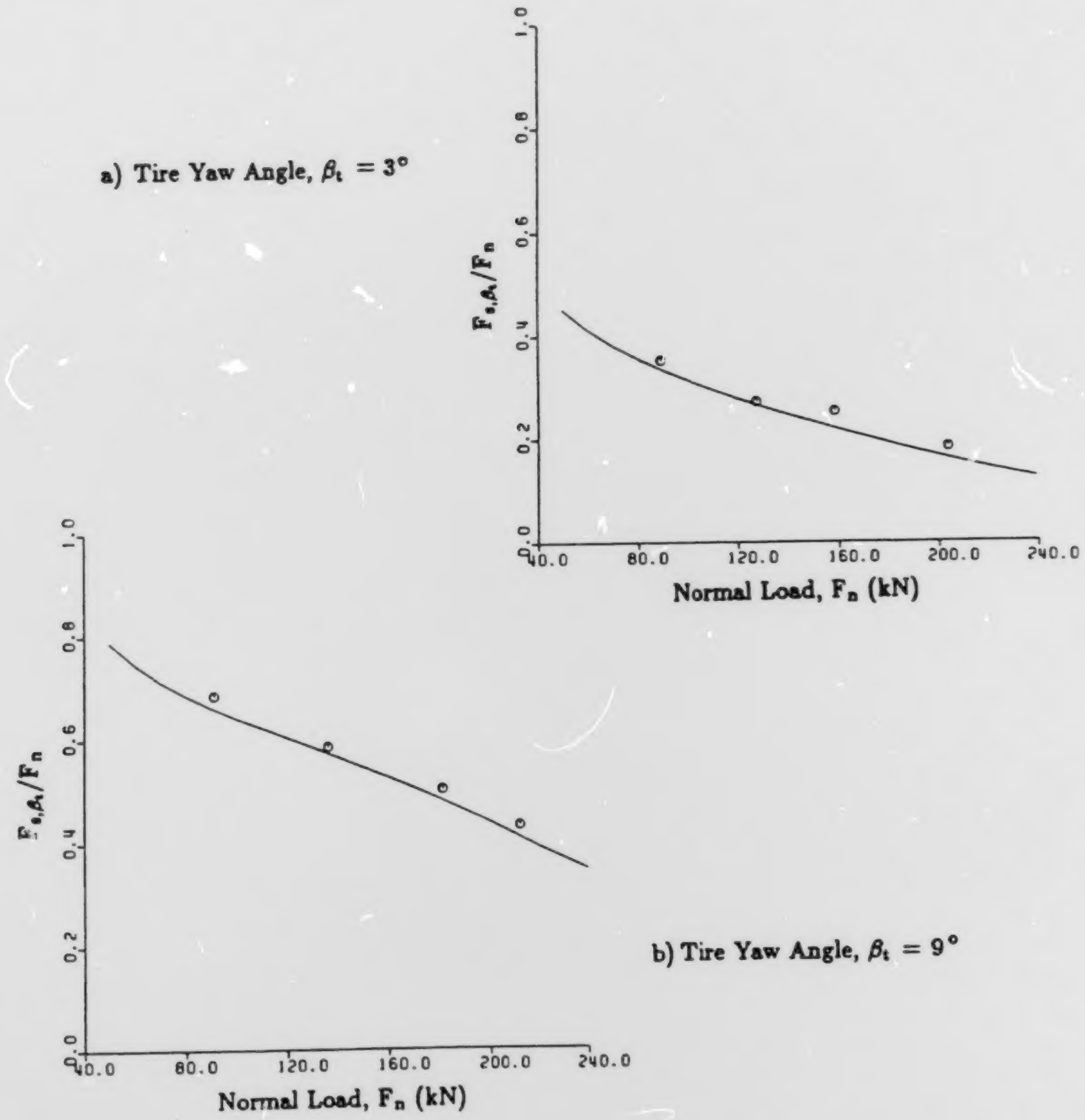


Figure 3.31 Tire Yaw Angle Effects on the Maximum Braking Coefficient of Friction for a 20" X 4" Tire on a Dry Runway at ≈ 2.5 m/s

Source: Ref. 72, Fig. 5.8

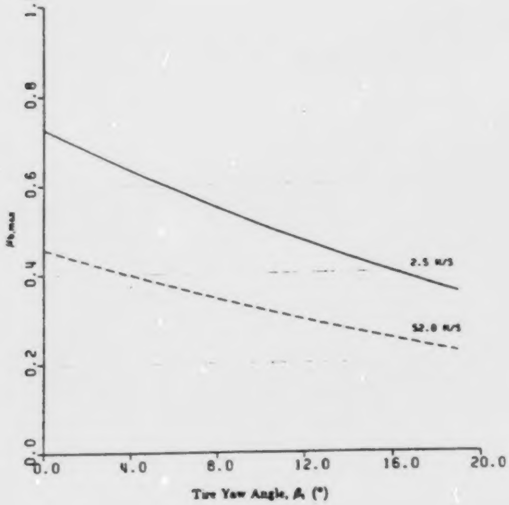


— Equations from Tire and Friction Models

ʘ Data from Tanner et al (1981)

Figure 3.32 Normal Load (F_n) Effects on Yaw Side Force (F_s,Bt) of a 49" X 17" Tire (V = 38.6m/s, V_{ref} = 60m/s)

Source: Ref. 72, Fig. 5.7



(1.3×10^4 N load, rated pressure, 160μm runway texture depth)

Figure 3.33 Variation in Braking Friction with Yaw Angle for a 46" X 16" Tire Using Equation (5.14)

Source: Ref. 72, Fig. 5.9

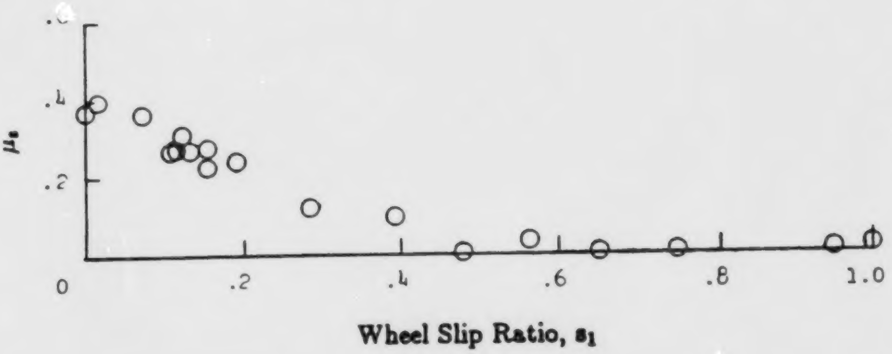
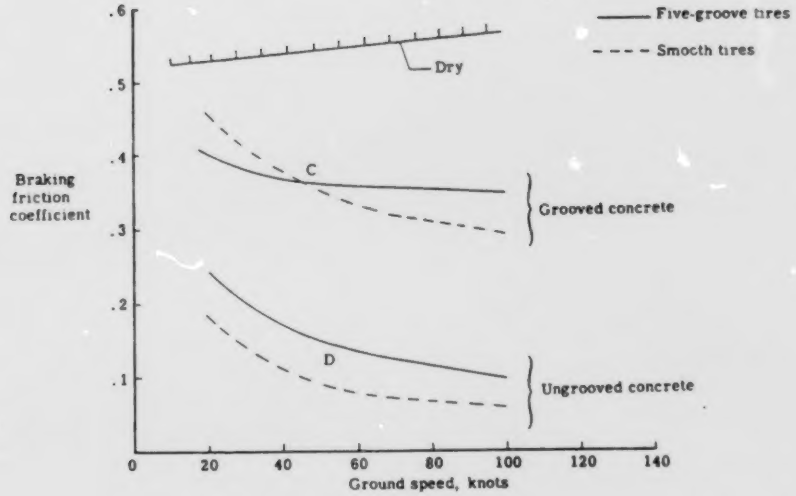
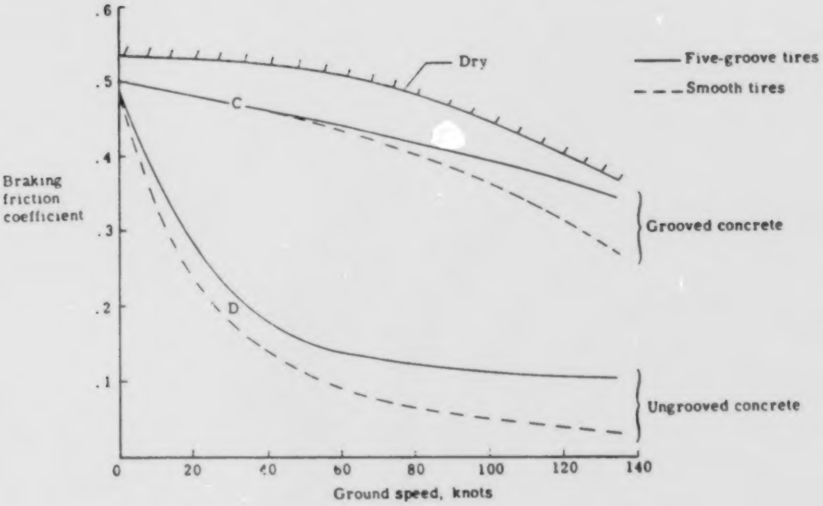


Figure 3.34 Typical Variations in Side Friction with Wheel Slip (Dreher and Yager (1976))

Source: Ref. 72, Fig. 5.10



(a) C-141A.



(b) 990A.

Figure 3.35 Tire-tread Effects on Wet and Puddled Runways for Twin-tandem Bogie Arrangements

Source: Ref. 13, Fig. 14

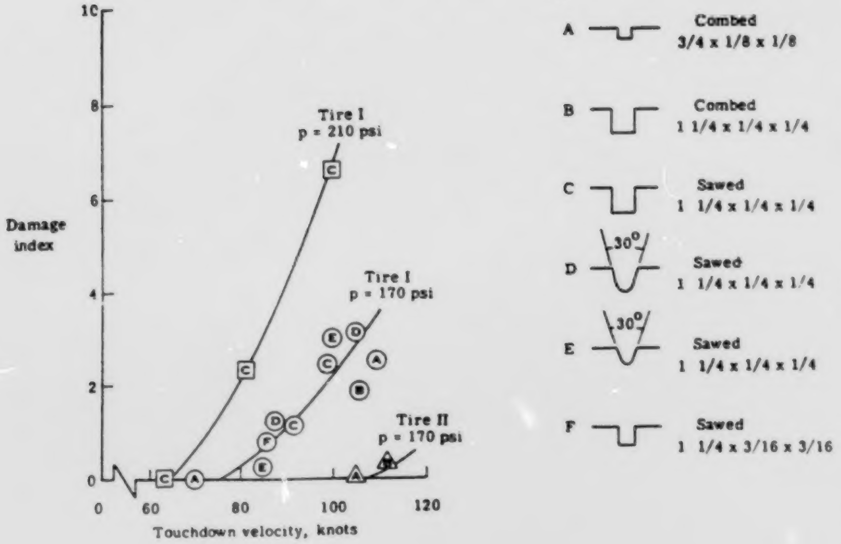
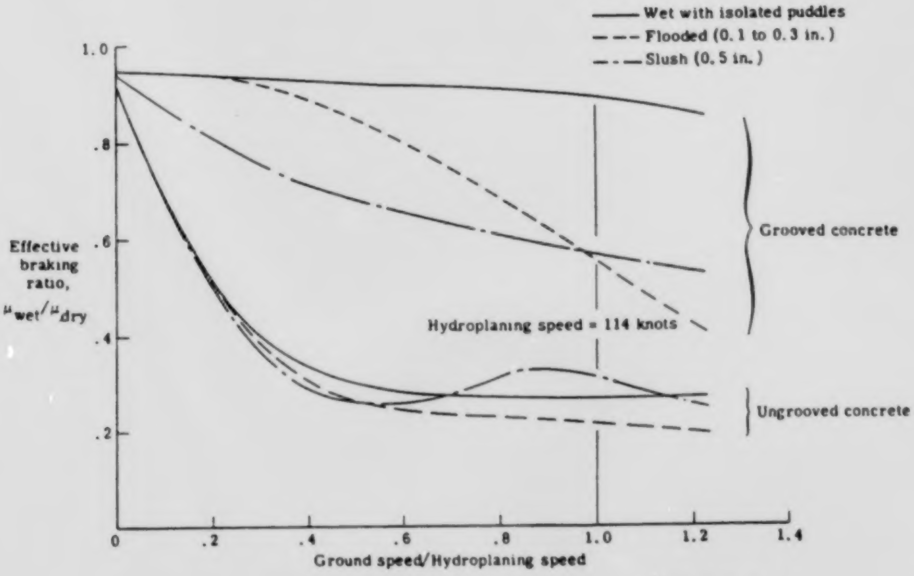


Figure 3.36 Tire Chevron Cutting on Grooved Surfaces. 49 X 17 tire; Vertical Velocity, 2.5 ft/sec. Measurements are in Inches for Runway Surfaces Unless Otherwise Noted

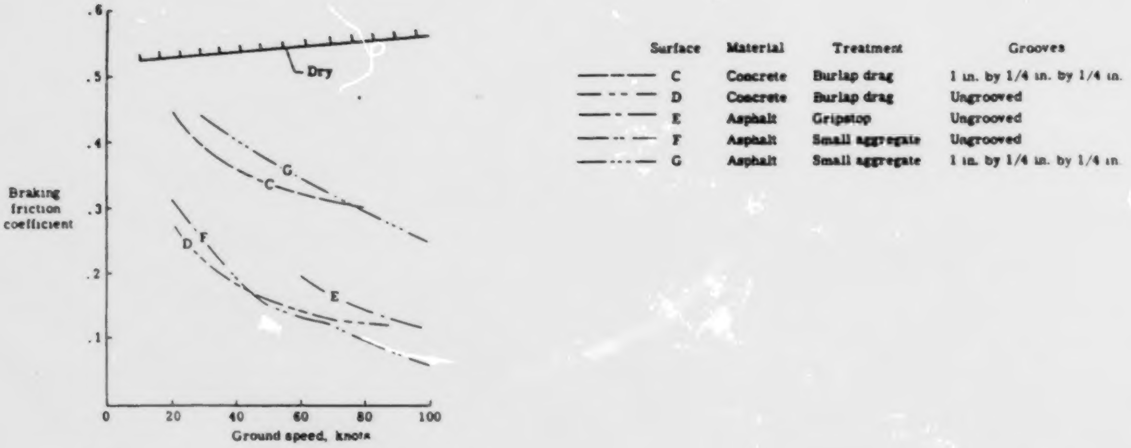
Source: Ref. 13, Fig. 28



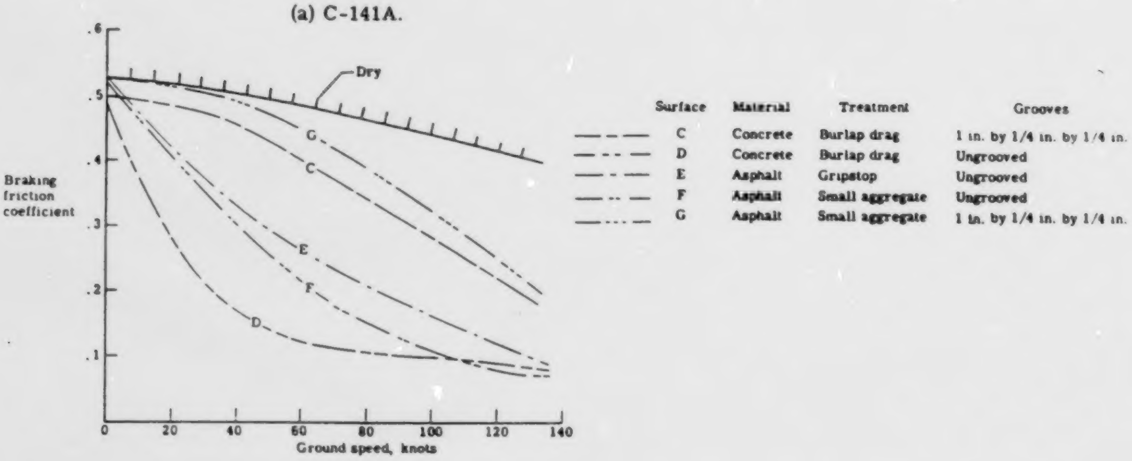
(a) 990A aircraft; five-groove tire; inflation pressure, 160 lb/in².

Figure 3.37 Effects of Runway Grooves on Aircraft Braking Performance

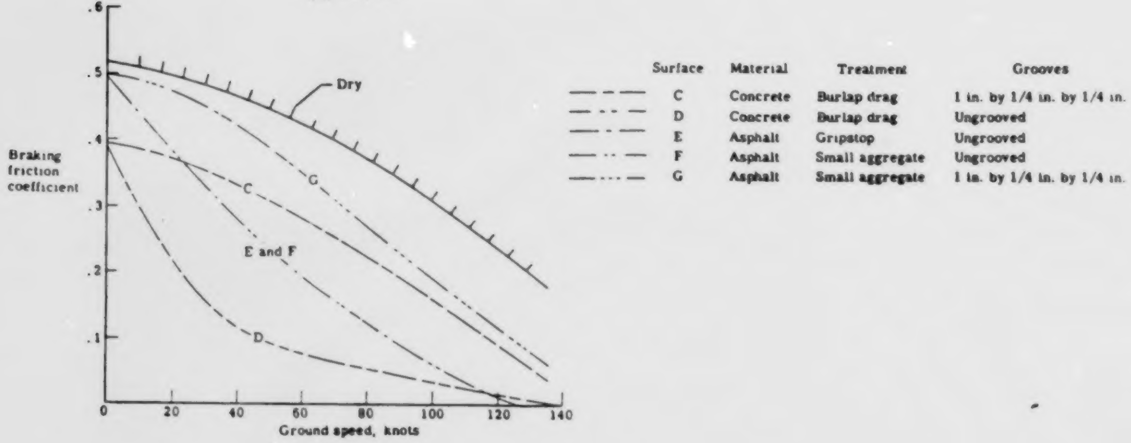
Source: Ref. 13, Fig. 27



(a) C-141A.



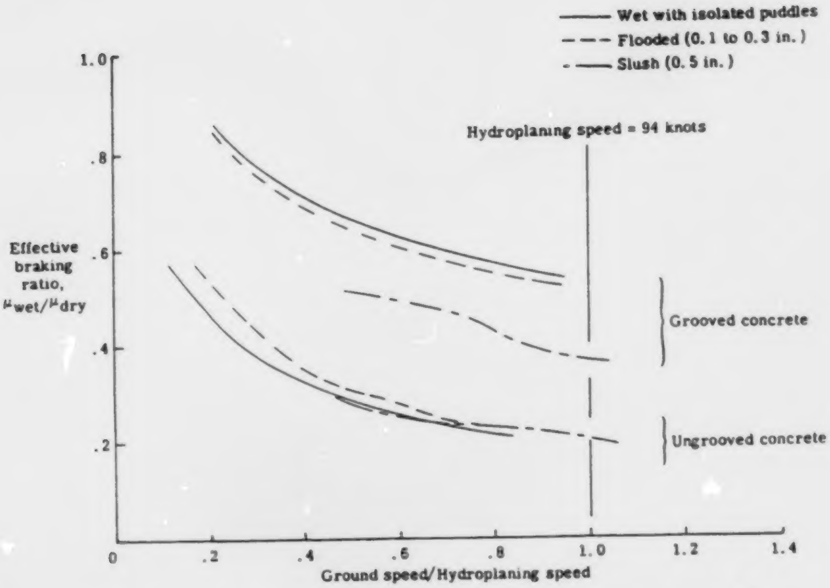
(b) 990A.



(c) F-4D.

Figure 3.38 Comparison of Braking Friction Coefficients on Flooded Runways (0.1 in. 0.3 in. water depth) for three aircraft

Source: Ref. 13, Fig. 13



(b) C-141A aircraft; five-groove tire; inflation pressure, 110 lb/in^2.

Figure 3.39 Effect of Runway Grooves on Aircraft Braking Performance

Source: Ref. 13, Fig. 27

including measuring the average texture roughness, and runway unevenness. In fact, it recommends in 3.2.1 four reasons to measure the friction value of a runway especially when wet. These are:

- to provide periodic calibrations of the value of the wet surface friction;
- to assess the slipperiness of the runway when wet;
- to determine the effect on friction when drainage is poor; and
- to determine the friction of runways that become slippery under unusual conditions.

States are recommended to specify a friction level below which it is required to take maintenance action. The Table 3.3 is in use in some States for new runways and the desired maintenance levels:

Table 3.3 Friction Levels for New Runways and the Desired Maintenance Levels

Test device	Design objective for new runway surface	Main-tenance level	Test Water Depth (mm)	Test Speed (km/h)
1	2	3	4	5
Mu-meter				
method 1	0.7	0.5	1.0	65
method 2	0.65	0.45	0.5	130
Skidometer	0.5	0.35	1.0	130 with high pressure tire
and Surface	0.6	0.4	1.0	95
Friction Tester	0.7	0.5 0.1		65
Stradographe	0.6	0.35	1.0	65

Source: ICAO Doc 9137-AN/898 Part 2

The values in columns 2 and 3 are averaged values representative of the runway or significant portions thereof.

Measuring and Estimating and Reporting Braking Condition is discussed at length in ICAO ASM Part 2 Chapters 4 and 5 with descriptions of friction measuring devices and the correlation possible between devices, plus a description of the SNOWTAM format.

Removal of Contaminants is described fully in the ICAO ASM Part 2 Chapters 7 and 8. The need for runway inspections and prevention of contamination are stressed, plus frequent measurement of friction to monitor surface conditions. When action is needed to remove snow, slush, ice, rubber, oil, grease via mechanical, chemical, and thermal methods. The use of sand is not encourage except under special circumstances and then as little as possible.

4. AEROPLANE TAKE-OFF PERFORMANCE

The introduction of large commercial jet transport aeroplanes with a considerable increase in take-off distances, led the airworthiness and operational elements of government regulatory agencies to introduce additional take-off performance requirements.

For the purpose of this report the main additional requirements dealt with the scheduling of the aeroplane take-off performance in such a manner as to provide for accelerate-stop distance within the runway length following a decision to abort the take-off prior to a speed to be defined as V_1. Also included in the requirements is the condition that the aeroplane have the ability to continue a take-off, with an engine failure, from the speed V_1 and clear a screen height of 35 feet at the end of the runway. There are several additional requirements that are imposed in meeting these two main requirements including the limits of the value of V_1, the speed at the screen height, etc., but these are not of particular concern at this time.

In Canada and the USA, the take-off performance, as identified in the aeroplane flight manual (AFM) or in an air carrier's operations manual, only addresses dry runway conditions and does not specifically address take-offs on contaminated runways. In many countries in Europe and in particular the United Kingdom and the Scandinavian countries, the scheduling of take-off performance for wet and slush covered runway conditions has been a requirement for many years, but only through their operating requirements. The requirements now include a reduction in screen heights from 35 to 15 feet for contaminated runway conditions.

In more recent times, the Joint Aviation Authority (JAA) has issued advisory material in support of the JAR 25 design standards which provides a means of demonstrating aeroplane take-off performance under various runway contaminated conditions if the aeroplane manufacturer wishes to have such performance approved for the aeroplane. The requirement to have such information remains within the operational requirements, but the means of showing compliance is in the airworthiness standards. The Japanese Airline and All Nippon

Airline prescribed take-off performance for their large jet transport in 1978 under both dry and contaminated runway conditions. Like Europe, the performance requirements were contained in the operational requirements and not in airworthiness standards.

In determining the take-off performance in terms of runway contamination, all countries who require such information take into consideration the change in runway friction and aeroplane drag, both as a result of the impingement of the contaminant on the airframe and of the displacement of the contaminant by tires, and the control of the aeroplane.

Credit for the use of reverse thrust in determining the accelerate-stop distance can be obtained if the appropriate airworthiness and operational requirements are met. However, few aircraft in Canada and the US have satisfied both requirements. In Canada only the BAC111 has met both requirements.

The lack of requirements in Canada for including the effect of runway contamination on take-off performance is not because there was a lack of information as to the effects of contamination on aeroplane take-off performance, nor was it because the Canadian operating environment is not conducive to such a need. It would appear that the operational safety record by Canadian commercial operators with large jet aeroplanes was, in the past, such that the regulators felt that there was no need to require such additional performance considerations. Canada has also tended to follow closely U.S. airworthiness and operating requirements, and in the area of take-off performance from contaminated runways, the FAA has not implemented specific requirements.

The impact of runway contamination on aircraft performance (both take-off and landing) has been studied, analyzed and flight tested since the late 1950's. As early as 1964, Ref. 9 lists 122 reference dealing with the subject of aeroplane performance, runway friction measurement and means of improving the determination of both. Ref. 5 states that for the period 1959-1964 there were 30 accidents/incidents in the USA attributed to runway contamination causing hydroplaning; Ref. 37 states that for the period 1981-1988 there were 400 runway traction related accidents/incidents in the USA.

Following an accident of an Ambassador aeroplane on the United Kingdom registry in 1958 which was related to an attempted take-off in slush, the United Kingdom investigated the effect of slush on the drag of an aeroplane during take-off (Ref. 6). They also investigated the impact of slush on several other types of aeroplanes, including jet bombers (Ref. 8). In the 1960's and early 1970's, flight tests were carried out by NASA using the Convair 880 and C-141 aeroplane to establish contaminate drag and the correlation between the stopping performance of a ground vehicle and the aeroplane under a wide variety of runway contaminates. In the 1970's Sweden and Japan investigated the effects of contaminates on several different types of commercial jet transport (Ref. 18, 25, 40, 50) and incorporated the results into the aeroplane flight manuals (Ref. 18, 18A). Finally, in 1988 NASA completed a five year project using a Boeing 727 and a Boeing 737 to establish the correlation between aeroplane effective friction and ground measuring vehicles (Ref. 52).

4.1 Civil Airworthiness Standards

In March 1952, the DeHavilland Comet aeroplane was the first commercial jet transport to enter into passenger service and with that entry, the concept of the critical decision speed V_1 and balanced field length (described in Section 4.3.2) was introduced for application on dry runway surfaces by the United Kingdom Authorities; no requirements were introduced at that time with respect to contaminated runways. Later, as other countries such as the USA introduced jet aeroplanes into commercial service, these same basic concepts were retained.

To-day there are two basic airworthiness requirements which govern the design standards for most large civil transport category aeroplanes: the USA FAR 25 and the European JAR 25. Both have very similar performance requirements governing the take-off performance, but only JAR 25 speaks to the subject of contaminated runway performance, even though the requirement for the performance data is governed by the operational requirements. Canada has adopted and adapted the USA FAR 25 as its basic design requirements and neither Canadian or the USA operating requirements contain requirements for contaminated runway take-off performance. In 1978, the FAA did issue guidance material in AC 91-6A for those operators who wished to consider the consequence of runway contamination on take-off performance.

4.2 The Effects of Runway Contamination on Take-off and Accelerate-stop Distances

The three main additional operational problems during the take-off and accelerate-stop procedure on contaminated runways are:

- the reduction in braking friction;
- the increase in drag due to undercarriage displacement of the contaminant and impingement of the contaminant on the aeroplane structure; and
- the directional control problem under any crosswind and/or engine failure condition.

The reduction in braking friction between the aircraft tire and the runway due to runway contamination is discussed in Section 3.3. The effect of the reduced friction on the take-off distance (TOD) is generally small, but very low friction can have significant effects on the accelerate-stop distance (ASD); examples are given in Section 4.4.

The increase in drag is due to energy required for the tires to displace the contaminant and due to the impact of the spray from the tires on the airframe. Both of these additional aspects caused by the contaminates are further complicated by the phenomena known as aquaplaning, which occurs when the speed of the tire through the contaminant is sufficient for the tire to lose contact with the surface in such a manner that it is entirely supported by the fluid itself. An example of this is the results of tests on a Convair 880 (Ref. 3) shown in Figure 4.1.

4.2.1 Displacement Drag

A general equation for determining the displacement drag for an individual tire rolling in water, given in Ref. 3, is as follows (note symbols used in Ref. 3 differ: $V = V_H$);

$$D_S = \tfrac{1}{2}\, C_{Ds} \quad p \quad \sigma \quad V^2 \quad d \text{ x } w \tag{1}$$

where D_S is the displacement drag due to contaminant,
C_{Ds} is the tire drag coefficient,
σ is the specific gravity of the contaminant,
V is the ground speed of the tire,
w is the width of the tire at the contaminant level,
d is the depth of contaminant, and
p is the density of water.

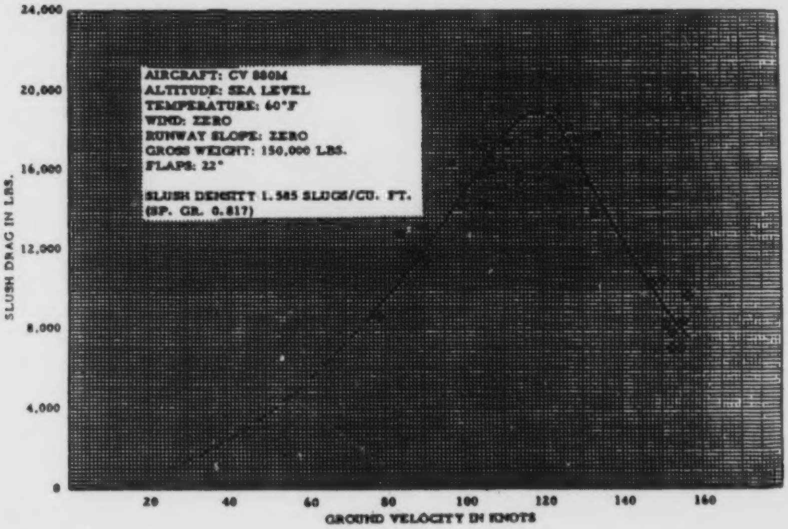


Figure 4.1 Slush Drag Forces on a Convair 880M Aeroplane for 1.0 Inch Normalized Depths

Source: Ref. 3, Fig. 46, Page 81

This equation is based on the assumption that the retardation force developed by an unbraked tire rolling on a slush- or water- covered runway surface varies directly with the square of the forward velocity and the first power of the tire frontal area exposed to the slush or water and the slush or water mass density. It is also assumed that tire aquaplaning effects on the retardation force may be disregarded. The tire frontal area exposed to the slush or water dependents not only on the width of the tire, but also on the deflection of the tire and Ref. 2 gives the following improved method of determining the displacement drag (note symbols used in Ref. 2 differ: $D_s = F_{x,g,f}$, $d = d_1$, $V = V_H$, $C_{Ds} = C_D$)

$$D_s = \tfrac{1}{2}\, C_{Ds}\ \rho\ \sigma\ d\ f(w)\ V^2 \qquad (2)$$

where f(w) is the chord length at the contaminant depth and can be expressed as follows;

$$f(w) = b = 2w \left[\frac{\delta + d}{w} - \frac{(\delta + d)^2}{w^2} \right]^{\frac{1}{2}} \qquad (3)$$

where δ is the tire deflection due to a pure vertical load.

Ref. 2 shows several examples where good correlation was found between observed and predicted values based on equations (2) and (3). These are given in Appendix C.

The interference between a pair of tires rolling in water increases rapidly as the tire spacing decreases when the distance between the tires is less than twice the tire widths. This is shown in Figure 4.2 based on scale tests in Ref. 10. The interference effect is partly due to the increased pressure required to force the water through the gap and partly due to the inter-wheel spray impinging on the wheel and axles.

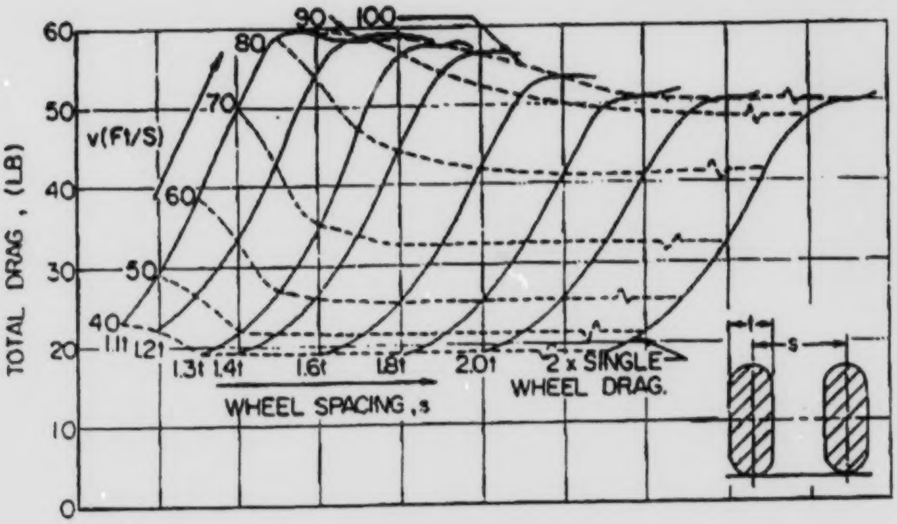


Figure 4.2 Total Drag of Two Wheels Side-by-side; 2 x 9 in. Smooth Tires on Smooth Belt; p = 30 psig; load = 200 lb./wheel; d= 0.20 in.

Source: Ref. 10, Fig. 17

Ref. 15, JAR AMJ 25X1591, states that an acceptable means of compliance in determining landing gear displacement drag is to assume a $C_{Ds} = 0.75$ for an isolated tire, a C_{Ds} of 1.6 times the isolated tire value for a typical dual wheel trailing arm arrangement and a C_{Ds} equal to 3.35 times the isolated tire value for a four wheel bogie. These values include any interference effect between the tires.

4.2.2 Impingement Drag

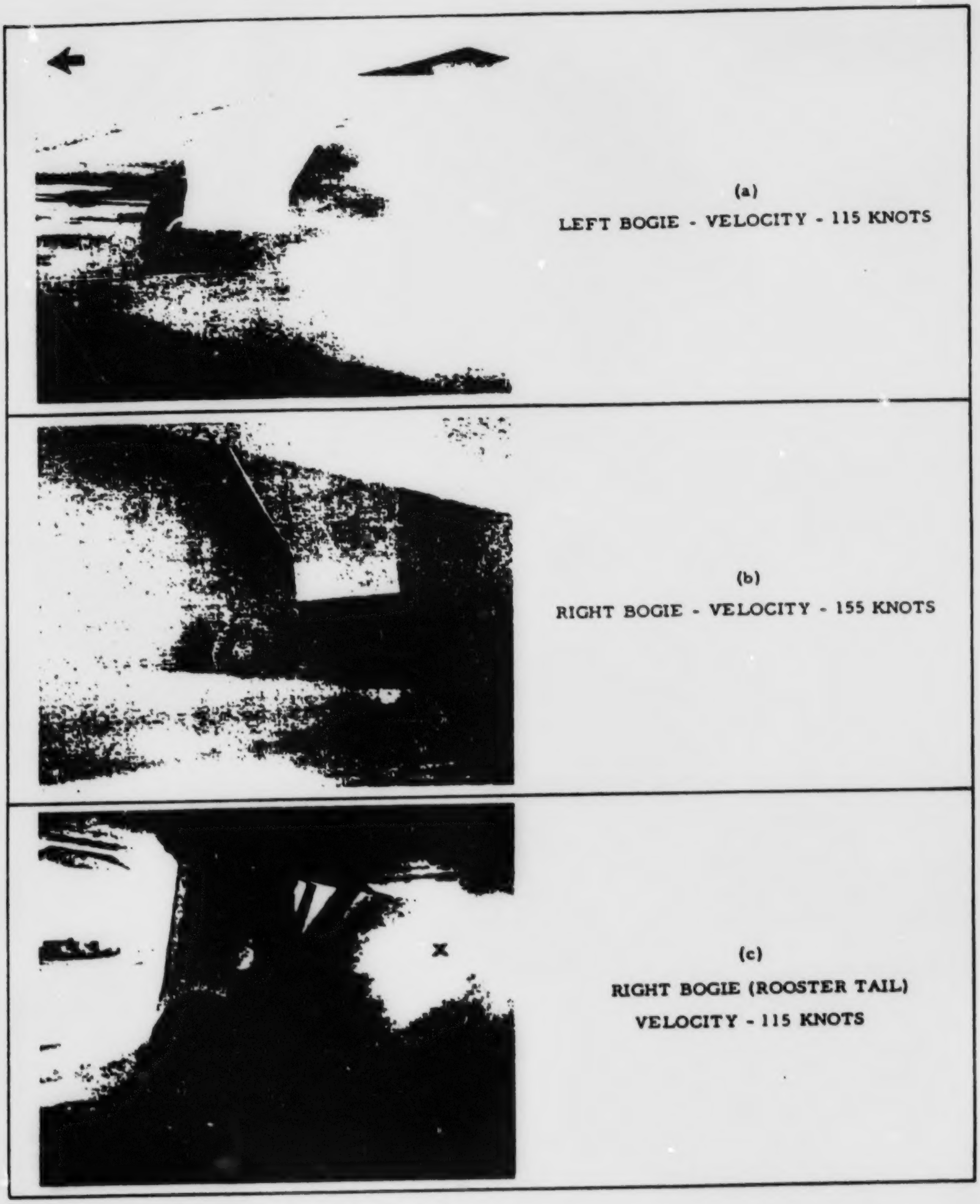
(a) Spray Patterns

The contaminant displaced by the tires is not gently pushed to one side, but is projected upward and sideways with considerable force. Near the tire the contaminant is thrown up as a jet, but further away it breaks up into a spray. This spray not only increases the aeroplane drag as it impinges on the airframe, but can also cause structural damage and has the potential of causing engine injection problems.

Spray patterns have been analyzed for a number of aircraft (Refs 3, 8, 18b, 15) and were found to vary to some extent with aircraft type. The longitudinal and lateral spray patterns are essentially independent of aeroplane speed for most aeroplane types. The vertical height of the spray increases with speed to a maximum just before aquaplaning speed. The spray thrown up by the nose wheel impinges on the main wheels and the lower surface of the fuselage. Very little of the main wheel spray impinges on the wing or wing flaps for most aircraft types, but for the BAC 111 there was considerable impingement from the main wheels at low speeds. The amount of spray was found to increase with depth of contaminant. Examples of the spray patterns are given in Figures 4.3 and 4.4 (from Refs 3 and 6).

Ref. 15, JAR 25, AMJ 25X1591, states that the plume rises longitudinally generally between 10^{o} - 20^{o} and varies rapidly with speed and depth of contaminate and to a small degree with the tyre geometry. Ref. 16, which is referenced in Ref. 15 as an acceptable method of determining spray patterns, provides for a method of estimating spray envelopes with a defined height, width and location of the side spray from a single side by side tyre arrangement. This method is based both on model and full scale tests, some of which are referred to above, and allows for variation in water depth, aeroplane speed and tyre deflection.

During tests on the Convair 880, Ref. 3, tests were carried out with the nose wheel in and out of the slush bed and from these tests it was determined that a $C_{Ds} = 1.6$ could be used for the aeroplane, a $C_{Ds} = 1.4$ for the main wheels and a $C_{Ds} = 2.6$ for the nose wheels. These values were established by using a $C_{Ds} = 0.75$ for tyre displacement drag, as described from Ref. 2.



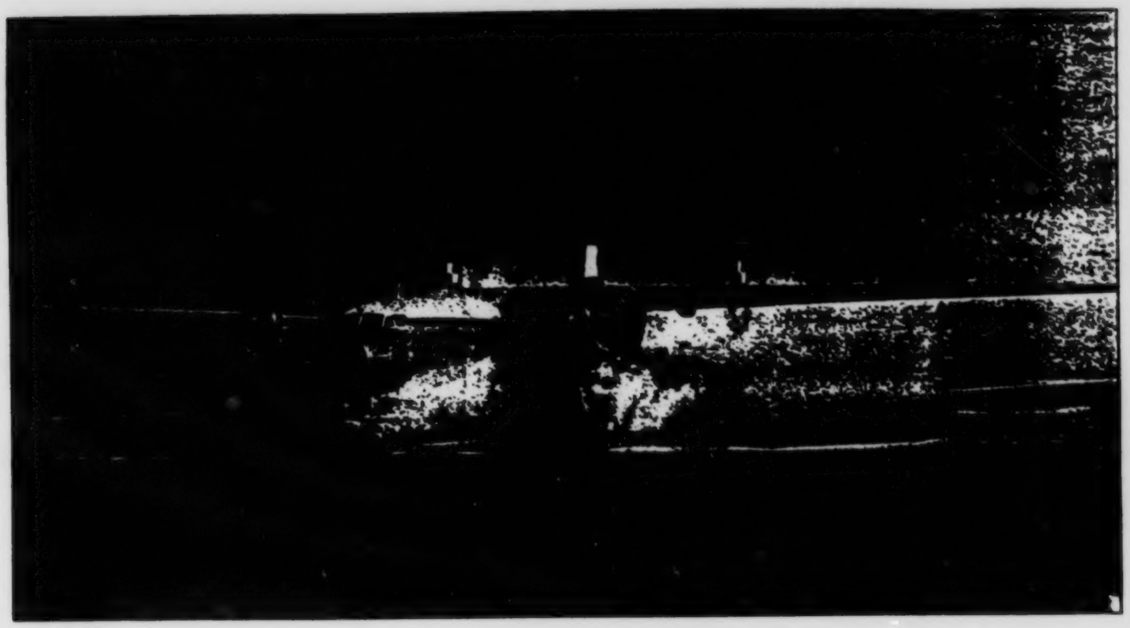
(a)
LEFT BOGIE - VELOCITY - 115 KNOTS

(b)
RIGHT BOGIE - VELOCITY - 155 KNOTS

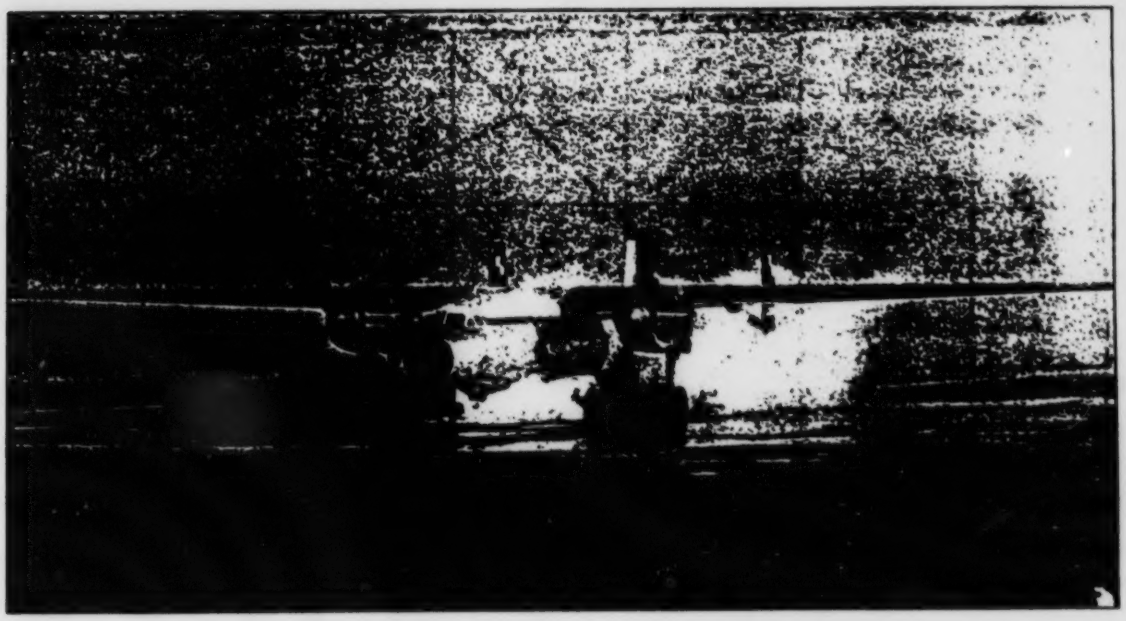
(c)
RIGHT BOGIE (ROOSTER TAIL)
VELOCITY - 115 KNOTS

Figure 4.3 Slush Spray Patterns for the Main Wheels of a Convair 880 in 1.4 Inches of Slush

Source: Ref. 5, Fig. 27



(a) Spray patterns before aquaplaning



(b) Spray patterns after aquaplaning

Figure 4.4 Spray Patterns for the Ambassador Before and While Aquaplaning

Source: Ref. 6, Figures 9 and 10

(b) Impingement Drag Calculations

Impingement drag, as a separate component of the total contaminant drag, is difficult to establish from tests since it is in integral part thereof. However, much work has been carried out in this direction.

Ref. 15, provides for an acceptable means of estimating impingement drag in lieu of full scale tests by using the following equation;

$$C_{Ds} = 8 \times L \times 0.0025 \qquad (4)$$

The spray drag coefficient C_{Ds} is based on a skin fiction drag coefficient of 0.0025. The C_{Ds} applies to the total nose-wheel displacement area and L is the length of the fuselage behind the point at which the top of the plume reaches the height of the bottom of the fuselage. The relationship given by equation (4) can also be used in the case where the main wheel spray strikes the rear fuselage, but it is only the inner plume from the innermost wheel that is involved. The displacement area is ½ that of one main wheel, but both sets of main wheels would contribute to the drag. This approach is only available when there are no large areas normal to the flow such as flaps, otherwise the approach developed in Ref. 16 applies.

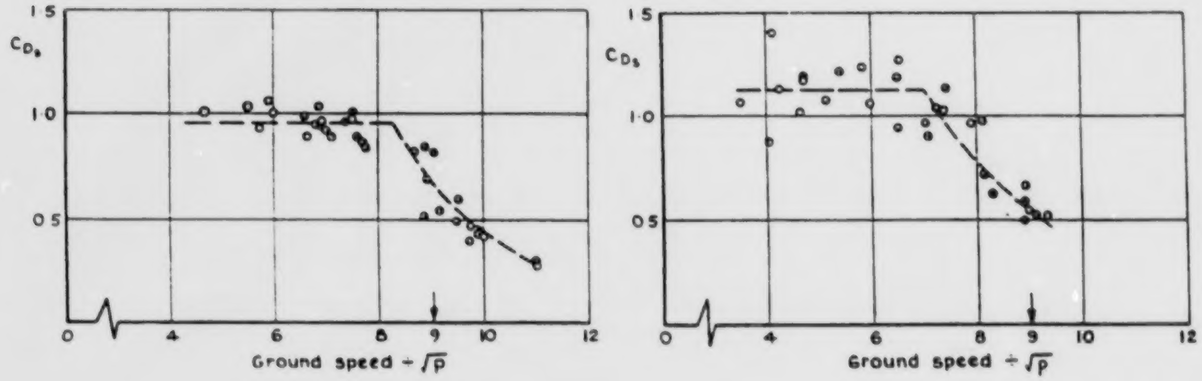
4.2.3 Total Contaminant Drag

Total contaminant drag can be estimated by summing the estimates of displacement drag and the impingement drag given in Sections 4.2.1 and 4.2.2.

A change in drag caused by one form of contaminate compared to another can be related without further tests being conducted if the contaminate's specific gravity is taken into effect (Ref. 6).

For any particular aeroplane configuration, the total contaminated drag coefficient C_{Ds} is essentially constant at all speeds up to the point at which aquaplaning occurs and then reduces linearly thereafter. Examples of this are given in Ref's. 3, 6, 8 and 18B. Further discussion and material drawn from the literature on contaminant drag is given in Appendix C.

Tests conducted on the Ambassador aeroplane, (Ref. 6), showed that the total contaminant drag ranged from $C_{Ds} = 1.03$ to 0.93, depending on the aerodynamic lift coefficient for the tests. Figure 4.5 shows how C_{Ds} varies for two different aeroplane types. Table 4.1 provides a summary of how contaminant drag varies with aeroplane types, various weights and undercarriage configurations. The Canberra is a low wing jet bomber and has a dual nose wheel and a single main wheel. The Viscount and Ambassador have dual nose and main wheels with the Viscount being a turboprop low wing and the Ambassador being a turboprop high wing. The Convair has dual nose and bogie mains and is a low wing jet aeroplane. The ARGOSY is a low wing, 4 reciprocating engine transport with single nose wheel and dual main gear. Measurement of the C_{Ds} values is difficult and there is a fair degree of scatter in the measured values.



(a) Ambassador: all wheels (b) Viscount: main wheels

Figure 4.5 Slush Drag Coefficient, C_{Ds}, In Terms of $V/\sqrt{P}$ (P is the Ground Contact Tire Pressure)

Source: Ref. 8, Fig. 17, Page 12

Table 4.1 Summary of Measured Slush Drag Coefficients Measured Speeds Below the Aquaplaning Speeds

Aircraft	C_{Ds}			Weight range, lb	Reference
	Main	Nose	Total		
Isolated wheel	-	-	0.7-0.75	-	Ref. 2
Convair 880	1.3	2.6	1.6	150 000 average	Ref. 3
Canberra B2	0.84	1.1-1.6*	0.88	26 500-33 900	Fig. 11
Ambassador	0.94	1.5	0.93-1.03+	44 000-53 000	Figs. 7&8
Viscount	1.05-1.28+	1.13	1.09	44 000-59 000	Fig. 13
Argosy	0.94	1.5	1.09	78 000	Ref. 6

* Depending on load on nose wheel
+ Depending on weight

Source: Ref. 8, Table 5, Page 9

4.2.4 Aquaplaning

The aquaplaning speed of an aeroplane is defined as that speed at which the portion of the aeroplanes weight applied to the tire is completely supported by the hydrodynamic pressure of the fluid acting vertically on the tire. This causes the tire to lift off the runway surface and is supported by a thin layer of liquid. The force required to lift the tire free of the surface is defined (Ref. 11) as follows;

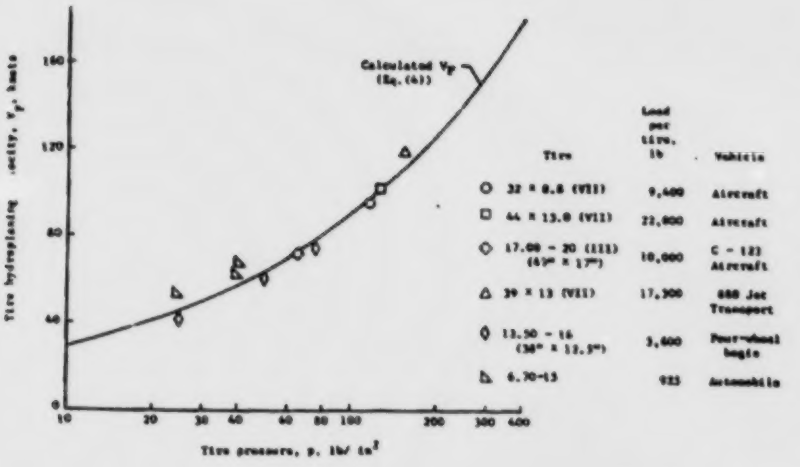
$$W = \tfrac{1}{2} C_L \sigma V_A^2 S_G \qquad (5)$$

where W is the weight of the aeroplane,
C_L is the hydrodynamic lift coefficient,
σ is the density of the fluid,
S_G is the tire contact area, and
V_A is the aquaplaning speed (knots).

Assuming that $C_L = 0.7$ and $W/S_G = P$ the ground contact tire pressure in lbs/sq in, then

$$V_A = 9 \sqrt{[P/\sigma]} \qquad (6)$$

This equation is basically recognized as defining the point of aquaplaning for aeroplane tires. A good example of its validity is demonstrated in Figure 4.6.



Experimental and calculated tire-hydroplaning velocities. (Data obtained from ref. 50)

Figure 4.6 Hydroplaning Velocities of Various Vehicles and Aeroplanes

Source: Ref. 7, Fig. 13, Note: $V_p = V_A$

The speed at which the tire loses contact with the runway, V_A, is not the speed at which maximum contaminant drag occurs (see Refs 3, 6 & 8). The maximum contaminant drag occurs somewhere between $V_A = 8 \sqrt{[P/\sigma]}$ an $V_A = 9 \sqrt{[P/\sigma]}$, but no agreement has been reached on the exact point. Figure 4.7 requires the C_{Ds} (C_D equivalent to C_{Ds} and $V_A = V_p$ in Ref. 15) to remain constant up to $V/V_A = 1$ followed by a drag coefficient reduction after this speed unless it can be shown otherwise. Boeing Co. Ltd proposed for the Boeing 767 aeroplane that a value for the constant be 8.628 and that the drag be reduced after the aquaplaning speed has been reached in accordance with the Convair 880 tests of Ref. 3.

At aquaplaning speed there is no friction between the tires and the runway and the distance required to stop the aircraft from above this speed increases greatly. An example of the effect of aquaplaning on the accelerate-stop distance (ASD) is given in Section 4.4.1 based on the B747 simulator tests.

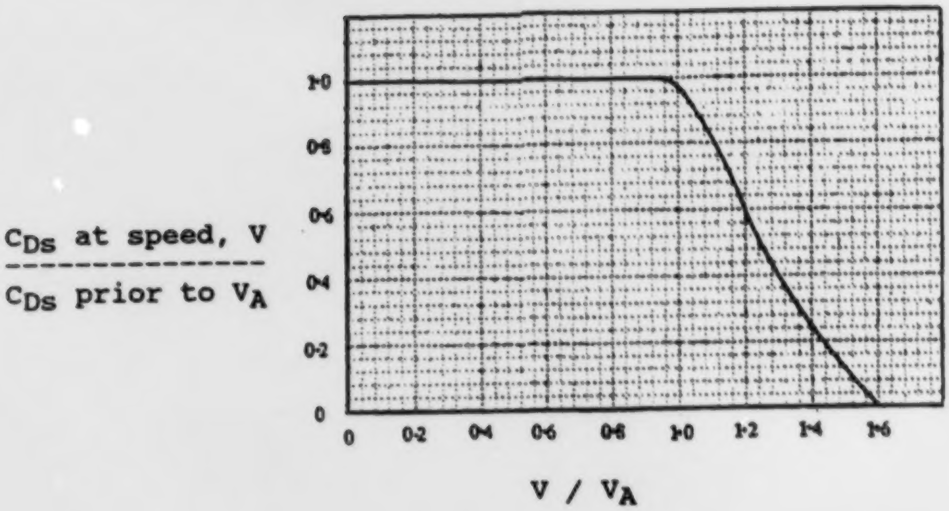
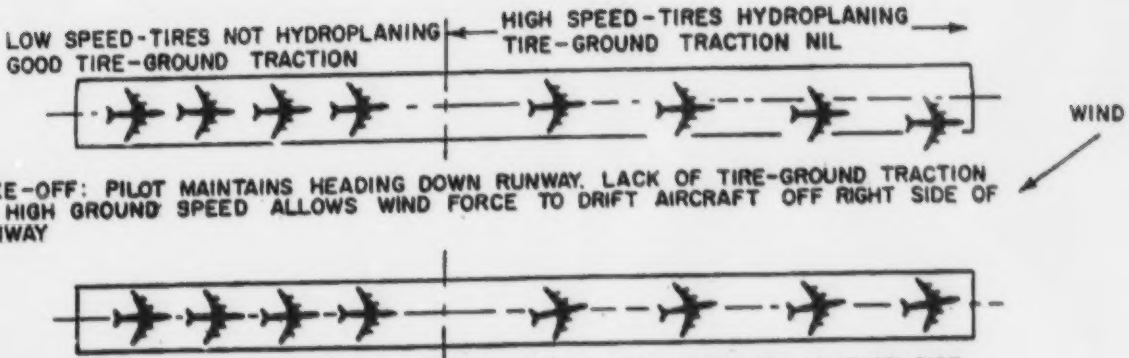


Figure 4.7 Effect of Speed on Slush Drag Coefficient (JAR)*

Source: Ref. 15, Fig. 3

4.2.5 Directional Control

The problem of maintaining directional control on contaminated runways is well stated in Ref. 5. "One of the worst control situations occurs when there is a cross wind in conjunction with water or slush covered runways and the conditions that are encountered produce hydroplaning. FAA-NASA tests with a four-engine jet transport in slush demonstrated a loss in directional control and an approximately doubling or tripling of the dry runway stopping distance without thrust reverse when hydroplaning occurred". It goes on to say that "as the aircraft approaches tire hydroplaning speed, tire-ground friction forces approach zero and a point is reached where the side force from the crosswind overcomes the counteracting tire-ground force. If runway heading is maintained the aircraft will skid toward the downwind side of the runway, see Figure 4.8(a). This downwind skid can occur even on a completely dry runway if the crosswind component is large enough. To prevent the drift, see Figure 4.8(b), the pilot yaws the aircraft into the wind so that the side component of engine thrust opposes the crosswind component, because tire-ground forces are not available for this purpose".


LOW SPEED-TIRES NOT HYDROPLANING
GOOD TIRE-GROUND TRACTION
HIGH SPEED-TIRES HYDROPLANING
TIRE-GROUND TRACTION NIL
WIND

A) TAKE-OFF: PILOT MAINTAINS HEADING DOWN RUNWAY. LACK OF TIRE-GROUND TRACTION AT HIGH GROUND SPEED ALLOWS WIND FORCE TO DRIFT AIRCRAFT OFF RIGHT SIDE OF RUNWAY

(B) TAKE-OFF: AT THE HIGHER GROUND SPEEDS, PILOT YAWS AIRCRAFT SO THAT SIDE COMPONENT OF ENGINE THRUST CANCELS SIDE THRUST ON AIRCRAFT DUE TO WIND. AIRCRAFT THEN PROCEEDS STRAIGHT DOWN RUNWAY.

Figure 4.8 Aircraft Reaction to Crosswind on Contaminated Runway

Source: Ref. 5, Fig. 3, Page 15

The crews task becomes very difficult when ground friction has disappeared or only sliding friction is available since only the aerodynamic and propulsive forces are available for the directional control of the aeroplane (Ref. 7). Based on their study, Ref. 7 states that "under conditions of crosswind and slick ground surface, minimum braking, or none at all, may be the best procedure to keep the aeroplane on the runway, since sliding friction acts to resist the motion, it does not provide a means for changing the direction of the motion. If rolling friction exists, then nose-wheel steering and lateral forces can be developed to displace the aeroplane. Under these circumstances, unless maximum deceleration is the decision, one might be better off to release the brakes in the forlorn hope that some rolling friction and cornering force might be available. Table 4.2 shows some desired actions depending on **where** you wish to leave the runway." Ref. 7's concluding remarks is "The lack of compatibility with the requirements for deceleration provides a critical problem for operational training and planning to keep accidents to a minimum".

Table 4.2 Configurations for Maximum Response

Deceleration	Lateral Displacement
Maximum drag	Minimum drag
Reverse thrust	Forward thrust
Heading parallel to runway	Heading above wind

Source: Ref. 7, Table 3

An example of the relationship between crosswind and runway friction obtained during the UTIAS B747 simulator tests is given in Figure 4.9. The line shows, for any value of friction μ, approximately the crosswinds above which the pilot will not be able to maintain directional control of the aircraft. In these particular tests a V_{mcg} of 111 kts was used to demonstrate the extent of the reduction in crosswind capability when changes to runway conditions from that used in the AFM to those associated with water, slush, snow and ice are encounter. The graph developed from these results compares favourably with those contained in the SAS Operations Manual for the B747 and clearly demonstrate the reduction in directional control as runway friction is reduced.

In Ref. 34a, All Nippon Airlines, provides the following information on flight operations for their B747;

"In consideration of having to possibly extend ground roll distances in the case of a crosswind conditions where use of thrust reverser and brake is restricted, the resistance to crosswind is much reduced during hydroplaning and slushplaning, the recommended maximum crosswind given in Table 4.3. have been set."

Section 4.4.3 provides additional indications on how crosswind capability is affected by runway contaminates for the Swedish Lingerflyg Airlines F-28.

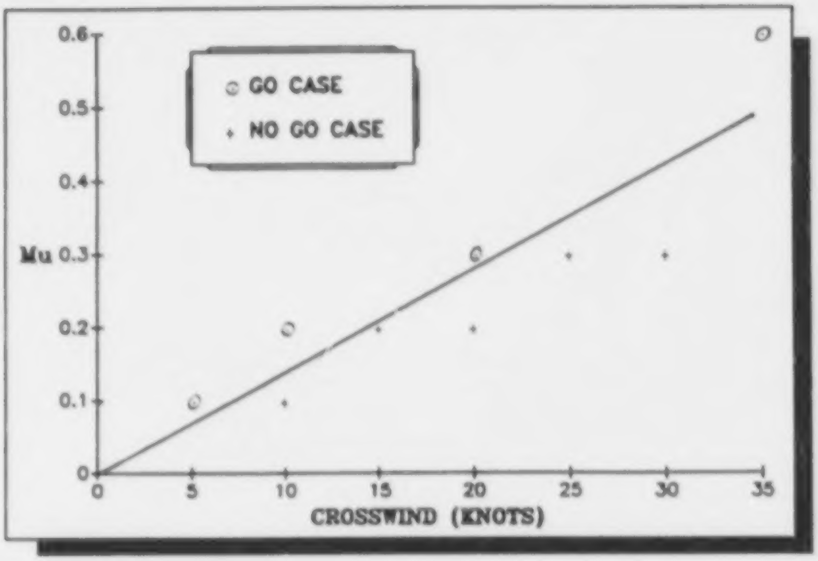


Figure 4.9 Directional Control Crosswind Limits at Various Levels of Friction for B747

Table 4.3 Recommended Maximum Crosswind for B747 Take-offs on Contaminated Runways

Runway Condition		Take-off or Landing	Runway Distance	Recomm. Max Crosswind
Flooded		Take-off and Landing	No relation to runway distance	10 Kt
Slush	2 mm or less	"	"	15 Kt
	3 - 12 mm	"	"	10 Kt
Snow, ice		Landing stage	In case or runway length of less than 3000 m	Braking action M.G.: 15 Kt MEDIUM: 15 Kt M.P.: 10 Kt

Source: Ref. 34a, Page 16

4.3 Required Runway Lengths for Take-off

An example of the airworthiness requirements governing the determination of the runway lengths required for take-off is shown in a graphical presentation in Figure 4.10 (from Ref. 21). For the purpose of this study, the benefits of clearways or stopways have not been considered.

4.3.1 Take-Off Equation

As previously stated, the aeroplanes take-off and accelerate-stop performance on contaminated runways is affected by the change in friction (μ), additional drag due to contaminant displacement by the types and impingement on the airframe, by controllability constraints and by aquaplaning.

In the case of only a μ change from the dry runway value to a contaminated runway value, the equations governing the determination of the accelerate-stop or take-off distances remain the same except for the value of μ. However, the decision speed may have to change in order to maintain a balanced field length or in order to maintain directional control.

When contamination depth is such that displacement and impingement drag must be considered, then additional drag terms must be added to the take-off equations and the aquaplaning speed under the particular conditions places a further limitation.

From the basic equations of motion for a aeroplane the take-off or accelerate-stop distances on non-contaminated runways can be derived from the following equation;

$$F_N - D_a - \mu\ [W - L] = W/g \times V \times dV/dS \qquad (7)$$

or

$$S = W/g \int_0^{V_x} V\ dV/(F_N - D_a - \mu\ [W-L]) \qquad (8)$$

where F_N is the take-off thrust,
D_a is the basic aerodynamic drag in take-off configuration,
L is the aeroplane lift,

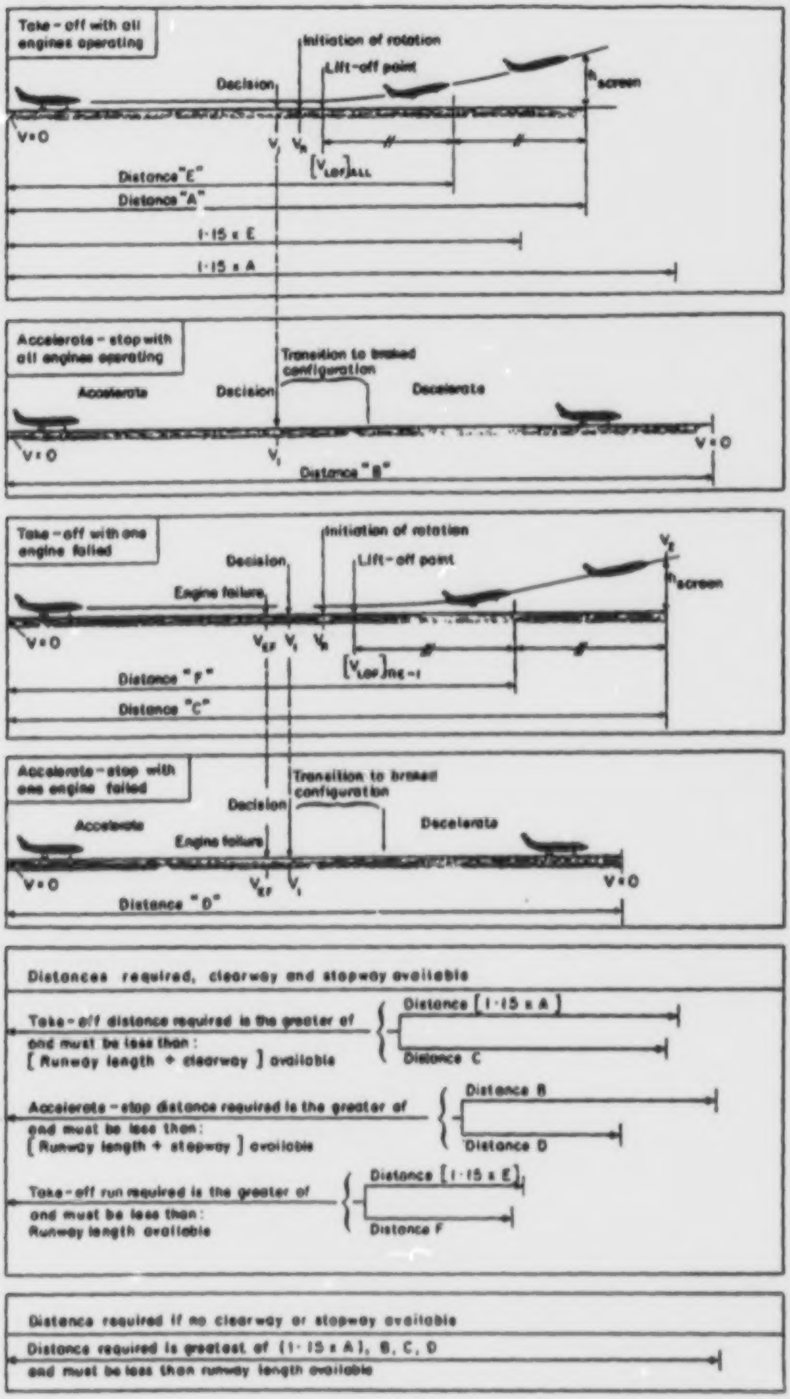

Take-off with all engines operating
Initiation of rotation
Lift-off point
Decision
h screen
V=0
V_1
V_R
$[V_{LOF}]_{ALL}$
Distance "E"
Distance "A"
1·15 x E
1·15 x A
Accelerate-stop with all engines operating
Transition to braked configuration
Accelerate
Decision
Decelerate
V=0
V_1
V=0
Distance "B"
Take-off with one engine failed
Initiation of rotation
Decision
Lift-off point
V_2
h screen
Engine failure
V=0
V_{EF}
V_1
V_R
$[V_{LOF}]_{NE-1}$
Distance "F"
Distance "C"
Accelerate-stop with one engine failed
Transition to braked configuration
Decision
Accelerate
Decelerate
Engine failure
V=0
V_{EF}
V_1
V=0
Distance "D"
Distances required, clearway and stopway available
Take-off distance required is the greater of
and must be less than:
[Runway length + clearway] available
Distance [1·15 x A]
Distance C
Accelerate-stop distance required is the greater of
and must be less than:
[Runway length + stopway] available
Distance B
Distance D
Take-off run required is the greater of
and must be less than:
Runway length available
Distance [1·15 x E]
Distance F
Distance required if no clearway or stopway available
Distance required is greatest of (1·15 x A), B, C, D
and must be less than runway length available

Figure 4.10 Determination of Runway Length Required for Take-off

Source: Ref. 21, Sketch 3.1, Page 13

W is the aeroplane weight,
g is the gravitational acceleration,
μ is the runway friction (as seen by aeroplane),
S is the distance,
V is the aircraft speed, and
V_x is the maximum speed to which particular conditions apply.

If contamination is present, equations (7) and (8) become

$$F_N - D_a - \mu\ [W-L] - D_s = W/g \times V \times dV/dS \qquad (9)$$

or

$$S - W/g \int_0^{V_x} V\ dV/(F_N - D_a - \mu\ [W - L] - D_s) \qquad (10)$$

where D_s is the additional drag due to contaminant and is the sum of the undercarriage displacement drag (Section 4.2.1) and impingement drag (Section 4.2.2). Note that D_a, L and D_s are all functions of the speed, V. These basic equations do not include other parameters such as wind, runway gradient, brake energy limits, etc.

These basic equations are applied in a segmented manner by dividing the take-off distance (TOD) or accelerate-stop distance (ASD) determination into various segments, an example of such a division is the one illustrated in Figure 4.11. In many applications of the equations, the distances need not be determined by integration when a mean value of F_N, D_a, D_s and L can be assumed, in which case Ref. 11 provides a ready means to estimate the distance values. However, modern aeroplane performance requirements, as set out in the airworthiness, Airplane Flight and Operational Manual requirements, and the desire of the manufacturer and operator to maximum performance, result in the integration method being used.

4.3.2 Balanced Field Length

Balanced field length is described well in Ref. 19. It states "This is the most frequently used measure of take-off performance when the effects of an engine failure during take-off are considered. The balanced field length occurs at the condition where, following an engine failure, the distance taken to abandon the take-off and to stop is equal to the distance taken to continue the take-off and to attain the

Description of Segment (see Appendix A for greater detail)	All engines operating		One engine failed	
	take-off	accel. stop	take-off	accel. stop
	A,E	B	C,F	D
	See Sections 3.2 and 3.3.			
Ground run with all engines operating, i.e. from start of take-off to first event (at V_{EF} or V_1 or V_R) in otherwise steady accelerating motion along ground.	✓	✓	✓	✓
Engine failure to decision point, i.e. short segment between V_{EF} and V_1, usually defined by demonstrated pilot reaction time, Δt_{rec} (see Sketch 3.1 in Ref. 5).			✓	✓
Decision point, i.e. this is not a segment but a reminder that the distances and times must be identified at which $V_c = V_1$ in engine-failed and all-engines-operating cases.		✓	✓	✓
Continued take-off ground run with one engine failed, i.e. from decision point (at V_1), following an engine failure (at V_{EF}), to the point at which rotation is initiated (at* V_R).			✓	
V_R to lift-off*, i.e. from speed at which rotation is initiated to point at which lift-off occurs (at V_{LOF}): all-engines and one-engine-failed cases must be calculated; lift-off usually defined by zero load on main wheels.	✓		✓	
Airborne segment to screen*, i.e. from lift-off (at V_{LOF}) until screen height is attained (at V_2, with one engine failed; at higher speed with all engines operating).	✓		✓	
Braked ground run, i.e. from decision point (at V_1), through sequence of pilot actions and powerplant, brakes, spoilers, etc responses (including any arbitrary time delays imposed by airworthiness requirements) to steady braked conditions and ending when the aeroplane stops.		✓		✓

Figure 4.11 Example of Segments Used to Define Take-off and Accelerate-stop

Source: Ref. 21, Page 19

safety speed V_2, at the screen height. The current, practical method of defining (and, during take-off of identifying) this condition is via the decision speed V_1, which is related to the engine failure speed.

Whether the balanced field length is viewed in terms of the continued or the abandoned take-off, the significant variables are the number of engines, and the speed V_1. The larger the number of engines, the smaller is the effect of one engine failure. The value of V_1 is determined by the ability of the aeroplane to accelerate after an engine failure relative to its ability to stop, when using the available (approved) means of retardation.

Owing to regulatory limitations on the range of values V_1 may take, it is not always possible to obtain a balanced field length. If a relatively high level of deceleration is possible, the value of V_1 required for a balanced field length may be greater than the rotation speed V_R and, since the regulations do not permit $V_1 > V_R$, the critical case becomes the continued take-off. If the available level of deceleration is relatively low or the thrust-weight ratio high, then V_1 for balanced field may be less than minimum ground control speed, which is not allowed, and the critical case is the abandoned take-off field length".

An exhaustive analysis of how to determine the TOD or ASD as a function of all the variables, including runway contamination, effects may be found in Ref. 21. As indicated in this reference, extensive knowledge of all the aerodynamic and thrust characteristics as well as the equation of motion of the aeroplane must be available before such a system can be applied. Ref. 21 also states that it is unlikely that a identical process would be followed for another combination of aeroplane and/or airworthiness requirements, however the fundamentals of this sophisticated approach would be maintained.

4.4 Aeroplane TOD and ASD Data

In order to establish the potential impact of applying additional requirements governing TOD and ASD on contaminated runways, it was necessary to establish the effect of contaminated runways on take-off distance, or take-off weight for a given take-off distance. Information was available from the Aeroplane Flight Manuals for a number of aircraft and was generated using a flight simulator at the University of

Toronto Institute of Aeroplane Studies (UTIAS) for the B747. The following information is not intended to be used in an absolute sense, it is used as a means of determining the order of the TOD or ASD performance change as a result of runway contamination so as to provide a basis for estimating the impact on the operators of jet aeroplanes from some example airports.

4.4.1 Boeing 747-100 Simulator Results at UTIAS

The UTIAS flight simulator is used for aerospace research and is basically configured as a Boeing 747 (B747) aeroplane in accord with NASA Reports CR114494 (1970) and CR1756 (1971). This configuration closely resembles a B747-100 aeroplane and formed the basis for estimating the affects of runway contaminates on the aeroplane's performance.

In obtaining data for the B747, no attempt was made to balance the field lengths and the TOD's were determined for a 35 feet screen since the Canadian airworthiness requirements do not provide for a reduced screen height under contaminated runway conditions, as is the case in Europe.

The extent of tests carried out, excluding any preliminary work up tests, is shown in Table 4.4. The values chosen were based on the weight limitations of the simulator at the time of the tests, a most likely headwind value for Canadian airports and runways, and braking coefficients and specific gravity of contaminants correspond to those contained within the various references reviewed. The tests which involved depths of contaminants deeper than 3 mm were run at approximately a constant specific gravity times depth value. The tests are described in Appendix D.

For the TOD tests, the engine thrust levels were set at the take-off target EPR values before the brakes were released and following the brake release the thrust levels were adjusted to target values again. V_1 and V_R values were taken from the AFM for the Boeing 747-100 for the test conditions, a horn provided the V_R reminder and a steady rotation was initiated such that the aeroplane would pass through 35 feet at the target V_2 speed. V_2 for all TOD tests was targeted at 1.25 V_s. All tests but one were performed with all engines operating.

Table 4.4 Tests Run on B747 Flight Simulator*

The following were fixed:	**Weights used:**
Dry $\mu = 0.60$	530,000 lbs
Flaps = 10°	680,000 lbs
Wind = 10 knot head wind	
Runway slope = 0°	
No reverse thrust	

Contaminant Type and and Depth	Braking Coeff.	Alt. = Sea Level				Alt. = 3,500 ft			
		OAT=-2°C		OAT=27°C		OAT=-2°C		OAT=27°C	
		ASD	TOD	ASD	TOD	ASD	TOD	ASD	TOD
Depth = 0	Mu=0.6								
	Mu=0.3		☒	☒	☒	☒	☒	☒	☒
	Mu=0.2			☒	☒	☒	☒	☒	☒
Water = 6 mm	Mu=0.3	☒	☒			☒	☒		
Slush = 8 mm	Mu=0.2			☒	☒			☒	☒
Dry Snow=20mm	Mu=0.2			☒	☒			☒	☒
Ice*	Mu=0.1		☒	☒	☒		☒	☒	☒

* Depth of ice set to zero for calculation of impingement drag; specific gravity set to 0.78 for slush and 0.35 for dry snow; Mu = μ.

For the ASD tests, a similar procedure for the start of the run was followed. At the decision speed V_1 the horn was sounded and the take-off was then rejected with the test pilot applying maximum brakes and simultaneously reducing thrust to idle as rapidly as possible; ground spoiler were deployed automatically by the simulator program. No attempt was made to simulate the time delays for the pilot recognition and actions incorporated in the AFM performance. As in the case of the TOD all tests but one were carried out without an engine failure and no reverse thrust was used. Although aquaplaning was predicted according to the previous equation, no adjustment of weight was used to avoid it and some of the ASD values reflect the consequences. Similarly, brake-energy limitations were exceeded, according to the AFM, but again weight was not reduced to cater for this.

One test was carried out simulating an engine failure at the minimum $V_1 = V_{mcg}$ value from the AFM. Both a TOD and ASD were carried out with 6 mm of water and a $\mu = 0.3$.

One set of tests was carried to determine the change in cross wind capability with variations in μ. The test conditions were 680000 lb weight, $h_p = 500'$, OAT = -2^0C and μ values were 0.1, 0.2, 0.3 and 0.6 with cross winds as high as 35 kts. The test pilot attempted to keep the directional deviation from the centre line to 25-30 feet and if he was unable to do so due to lack of directional control a "No" answer was recorded.

The results of the tests are summarized in the following graphs and the detailed results of all the tests are contained in Appendix D.

Figure 4.12 shows the accelerate-stop distances on a dry and a water (depth = 6 mm) covered runway for two take-off weights and altitudes. At high take-off weights the increase in ASD due to the standing water and aquaplaning is almost 12,000 feet at an altitude of 3,500 feet, but at low takeoff weights the increase is only 2,700 feet. The effect of standing water on TOD is much less with 6 mm of water increasing TOD by 1045 feet at a TOW of 680,000 lbs and an altitude of 3500 feet.

Figure 4.13 shows the change in acceleration with time during aborted take-offs at -2^0C on a dry runway and 27^0C on a water covered runway. The effect of aquaplaning on the deceleration rate of the aborted take-off on a water covered runway. The initial deceleration rate is only 2 ft/s/s when the aquaplaning occurs, but when the speed drops below aquaplaning speed of about 130 knots the deceleration quickly increases to 6 ft/s/s. On a dry runway the maximum deceleration rate is close to 12 f/s/s. The aeroplane travelled 5,400 feet in the 23 seconds while aquaplaning and the speed only dropped from 150 to 130 knots during that time.

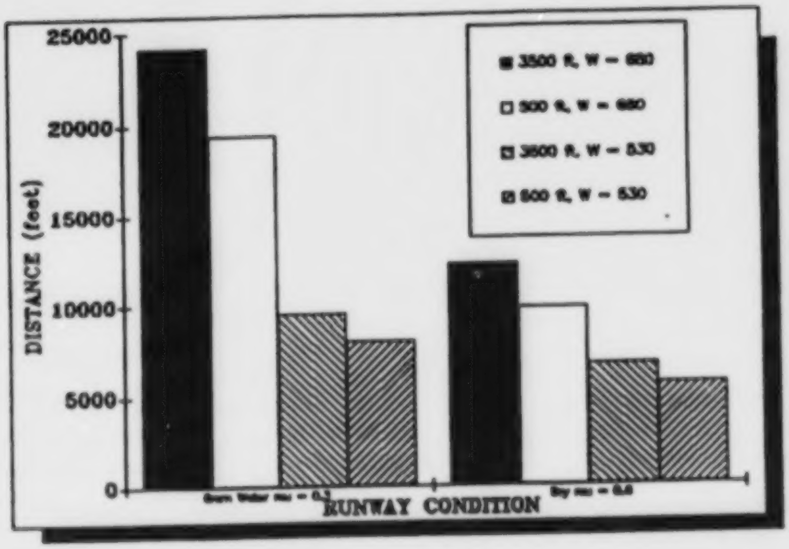


Figure 4.12 Accelerate-stop Distance for B747 on Dry and Water Covered Runway for Two Set of Weights and Altitudes*

* Weights, W, in 000's lbs, OAT = 27^{0}C, Mu = μ, V_1 speeds are 154, 152, 127 and 123 knots in order of conditions given in figure.

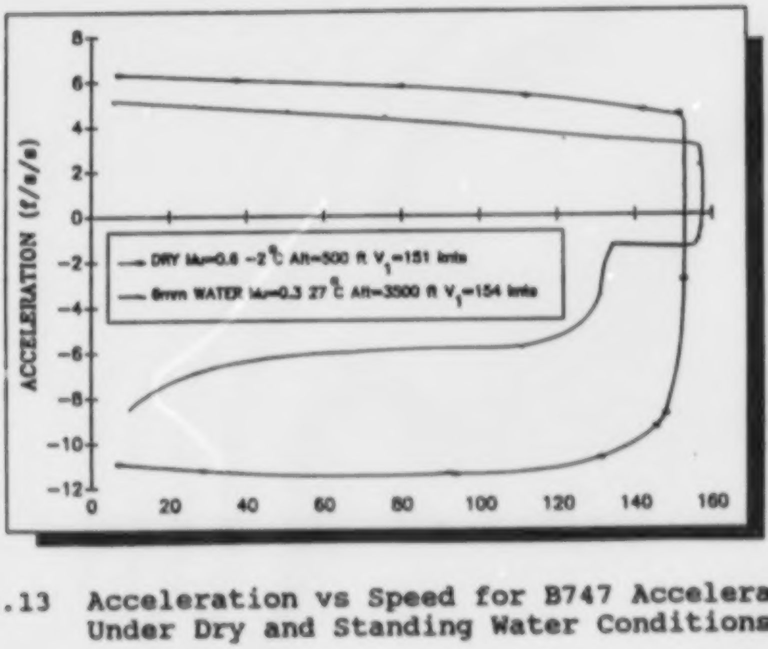


Figure 4.13 Acceleration vs Speed for B747 Accelerate-stop Under Dry and Standing Water Conditions

The test data indicates that runway contamination causes large increases in the ASD and TOD of the B747 as shown in Table 4.5.

Table 4.5 Increase in ASD and TOD due to Runway Contamination for the B747, Weight 680000 lbs, h_p = 500 feet, OAT=-2^0C, V_1=151 kts

Contaminant	Increase in Distance (feet)	
	ASD	TOD
8 mm of slush	3500	1230
20 mm of snow	3500	1126
<3 mm of slush	3150	500
ice	8350	
<3 mm of water	1200	

The effect of engine failure at V_1 speed on the TOD on a wet (less than 3 mm of water, μ = 0.3) runway was also tested using the B747 simulator and the results are shown in Figure 4.14.

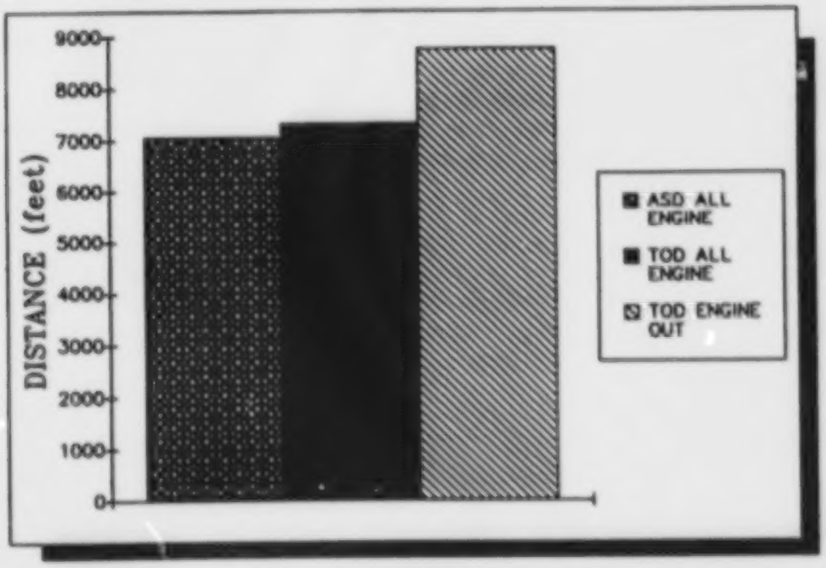


Figure 4.14 Take-off Distance With and Without Engine Failure and Accelerate-stop Distance for B747 on a Wet Runway

The effect of crosswind on the controllability of the aeroplane for various μ values was tested, as discussed in Section 4.2.5, and the results are shown in Figure 4.9.

4.4.2 Performance Data for the Airbus 320

Data for the Airbus 320 was obtained from the French Director General of Civil Aviation (DGCA) approved Flight Manual. The data was derived by Airbus Industries from flight tests and by analysis in conjunction with the AMJ 25X1591 (Ref. 19). A further description of the approach taken by Airbus in developing the data may be found in Ref. 24. The Airbus 320 take-off data were obtained for three ratios of, V_1/V_R (V_R is the rotation speed), but no attempt was made to balance the field length by adjusting the V_1 speed. Also, for contaminated runways, a reduced screen height of 15 feet was included in the determination of TOD and credit for reverse thrust was not included in the determination of ASD. Examples of the data obtained from the flight manual are given below.

Figure 4.15 shows the allowed maximum take-off weight (ATOW) for an A320 taking off from a 9,000 foot runway at -2^{0}C and V_1/V_R for three altitudes when the TOW is restricted by the ASD (i.e. ASD = 9000 feet). The ATOW capability under dry and wet conditions is greater than the certified MTOW of the aircraft (162,921 lbs) and this is therefore the upper weight limit. However, in slush and standing water conditions, the ATOW's must be reduced by 13,000 to 19,000 lbs for the aircraft to stop on the runway after aborting the take-off at V_1. Figure 4.16 shows the corresponding ATOW's limited by TOD. Half an inch of slush reduces the ATOW by 30,000 lbs.

The relationship between take-off weight and ASD and TOD (engine failure at V_1, reverse thrust not used in accelerate-stop) are shown for various winter runway conditions in Figures 4.17 and 4.18. Similar relationships for summer runway conditions is shown in Figures 4.19 and 4.20.

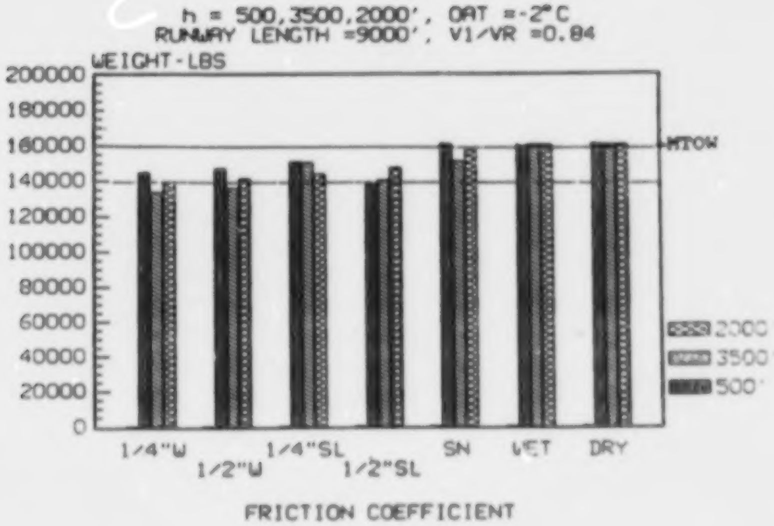


Figure 4.15 Effect of Runway Condition on ATOW When ATOW is Limited by ASD for A320 from 9,000 ft Runway at Three Altitudes (W = water, SL = slush and SN = snow)

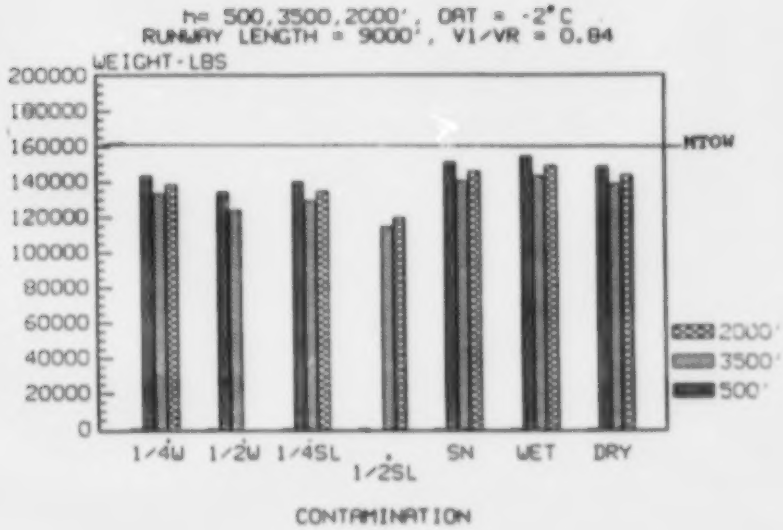


Figure 4.16 Effect of Runway Condition on ATOW When ATOW is Limited by TOD for A320 from 9,000 ft runway at Three Altitudes (W = water, SL = slush and SN = snow)

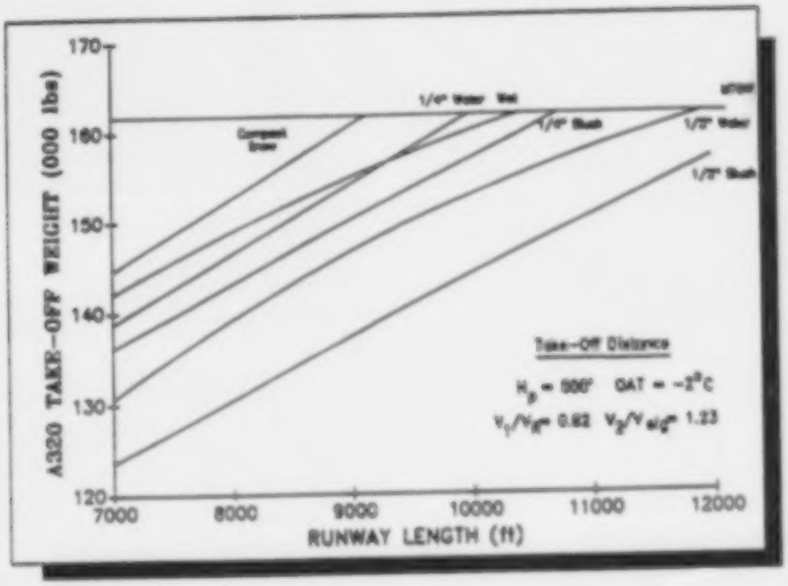


Figure 4.17 Take-off Distance vs Take-off Weight for A320 Under Various Winter Runway Conditions

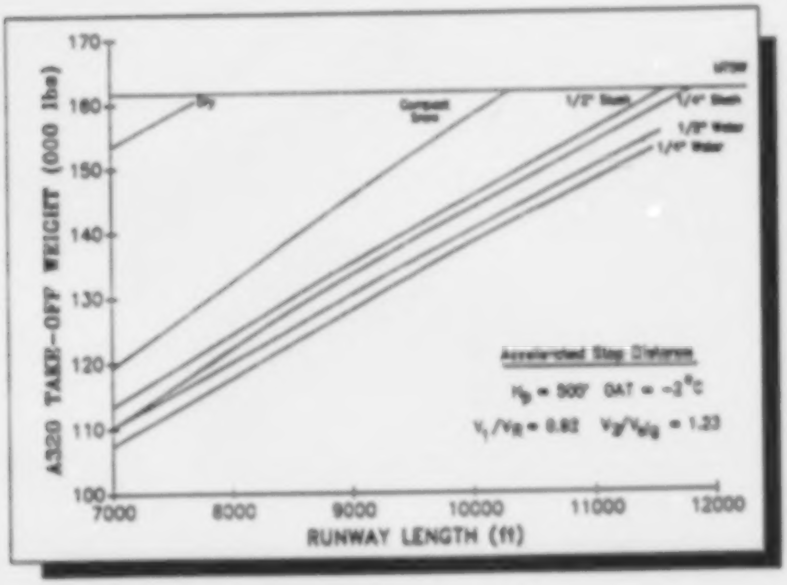


Figure 4.18 Accelerate-stop Distance vs Take-off Weight for A320 Under Various Winter Runway Conditions

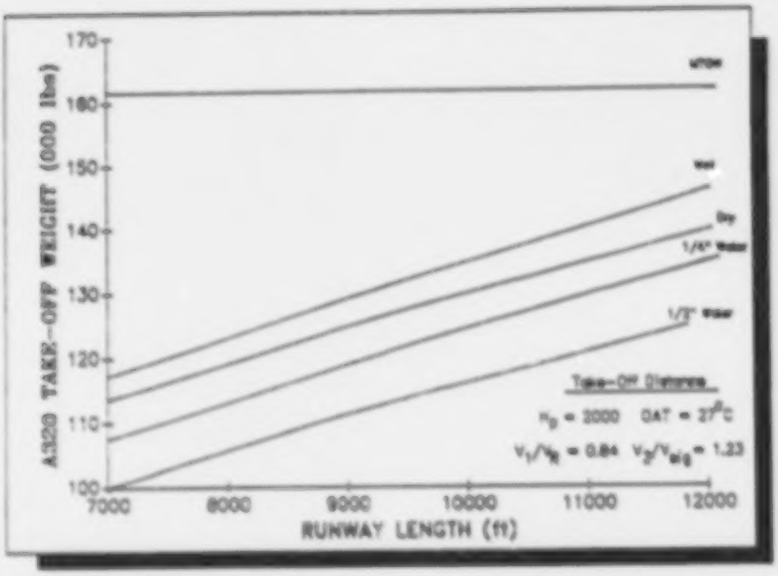


Figure 4.19 Take-off Distance vs Take-off Weight for A320 Under Various Summer Runway Conditions

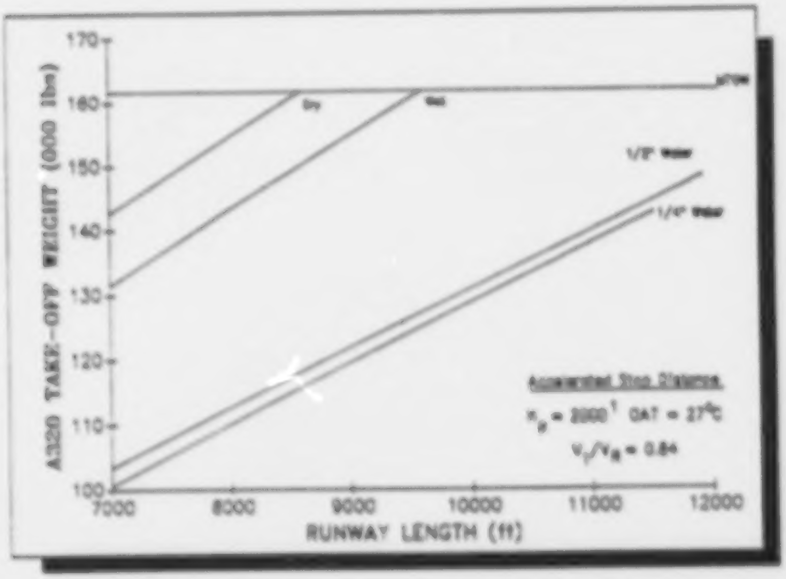


Figure 4.20 Accelerate-stop Distance vs Take-off Weight for A320 Under Various Summer Runway Conditions

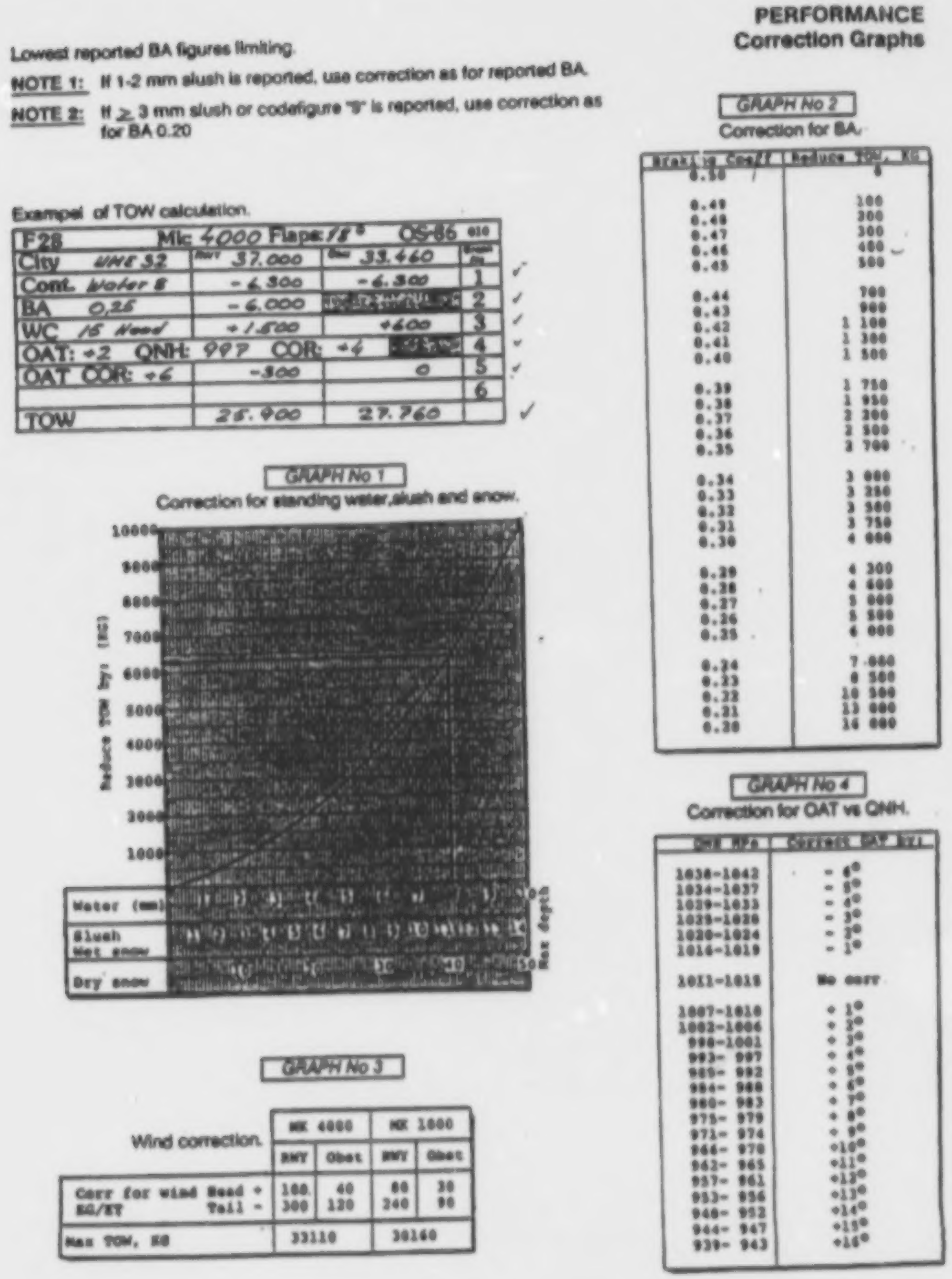
An example of the effect on ASD and TOD of various winter runway conditions is given in Table 4.6 for a particular set of conditions.

Table 4.6 ASD and TOD for A320 Under Various Runway Conditions with TOW = 150000 lbs, h_p = 500 feet, OAT = -2^0 C and V_1/V_R = 0.84

Runway Condition	ASD (ft)	TOD (ft)
All engine		
Dry	5581	6110
Engine Failure		
Dry	<6000	9200
Wet	6460	8460
Snow (Compact)	8069	8840
¼" Slush	9280	10820
½" Slush	8700	>12000
¼" Water	9500	9600
½" Water	9280	11800

4.4.3 Fokker F-28 Mk 1000 and 4000

Slush drag effects including undercarriage, impingement and friction effects for the F-28 aeroplane as operated by Linjerflyg Airlines of Sweden and approved by the Swedish Authority are as follows taken from Lingjeflyg AFM;



PERFORMANCE
Correction Graphs

Lowest reported BA figures limiting.

NOTE 1: If 1-2 mm slush is reported, use correction as for reported BA.

NOTE 2: If ≥ 3 mm slush or codefigure "9" is reported, use correction as for BA 0.20

Exempel of TOW calculation.

F28	Mic 4000 Flaps: 18°	OS-86	010
City UME 32	37.000	33.460	
Cont. Water 8	- 6.300	- 6.300	1 ✓
BA 0,25	- 6.000	[redacted]	2 ✓
WC 15 Head	+ 1.500	+ 600	3 ✓
OAT: +2 QNH: 997 COR: +4		[redacted]	4 ✓
OAT COR: +6	- 300	0	5 ✓
			6
TOW	25.900	27.760	✓

GRAPH No 1

Correction for standing water, slush and snow.

GRAPH No 2

Correction for BA.

Braking Coeff	Reduce TOW, KG
0.50	0
0.49	100
0.48	200
0.47	300
0.46	400
0.45	500
0.44	700
0.43	900
0.42	1 100
0.41	1 300
0.40	1 500
0.39	1 750
0.38	1 950
0.37	2 200
0.36	2 500
0.35	2 700
0.34	3 000
0.33	3 250
0.32	3 500
0.31	3 750
0.30	4 000
0.29	4 300
0.28	4 600
0.27	5 000
0.26	5 500
0.25	6 000
0.24	7 000
0.23	8 500
0.22	10 500
0.21	13 000
0.20	16 000

GRAPH No 3

Wind correction.

	MX 4000		MX 1000	
	RWY	Obst	RWY	Obst
Corr for wind Head + KG/KT Tail -	100 300	40 120	80 240	30 90
Max TOW, KG	33110		30160	

GRAPH No 4

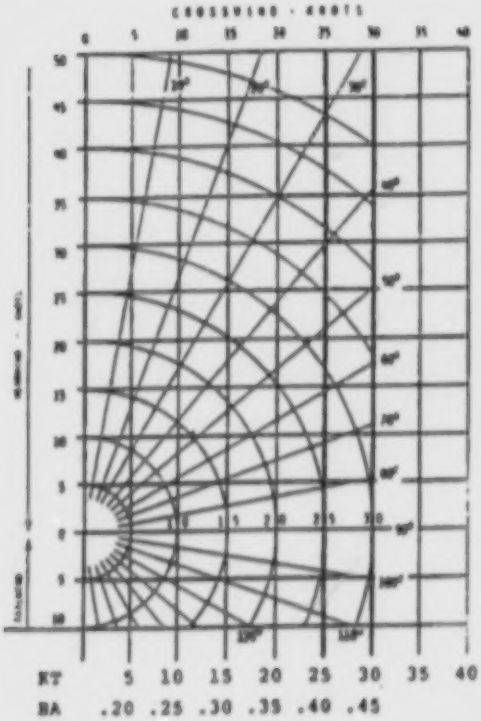
Correction for OAT vs QNH.

QNH HPa	Correct OAT by:
1038-1042	- 6°
1034-1037	- 5°
1029-1033	- 4°
1025-1028	- 3°
1020-1024	- 2°
1016-1019	- 1°
1011-1015	No corr
1007-1010	+ 1°
1002-1006	+ 2°
998-1001	+ 3°
993- 997	+ 4°
989- 992	+ 5°
984- 988	+ 6°
980- 983	+ 7°
975- 979	+ 8°
971- 974	+ 9°
966- 970	+10°
962- 965	+11°
957- 961	+12°
953- 956	+13°
948- 952	+14°
944- 947	+15°
939- 943	+16°

Figure 4.21 Performance Correction Graphs for Contaminated Runways Extracted from the Linjerflyg Operating Manual for the F-28

For example, if the same set of temperature, pressure and wind conditions apply, a weight penalty of 9400 kgs would be required for a take-off in 8 mm of slush with a runway friction of 0.25 compared with a dry, uncontaminated runway.

The maximum crosswind component, including gusts, as a function of runway friction is as follows:



CROSS WIND LIMITS

VS

BRAKING ACTION

Friction coef	Braking action	Crosswind limits (KT
0.45 or more	Good	30
0.40 - 0.45	Good	25 - 30
0.36 - 0.39	Medium/Good	21 - 24
0.30 - 0.35	Medium	15 - 20
0.26 - 0.29	Medium/Poor	11 - 14
0.20 - 0.25	Poor	5 - 10

Figure 4.22 Maximum Crosswind Component vs Runway Friction Extracted from the Linjerflyg Operating Manual for the F-28

Source: Ref. 18A, Page 4.96

4.4.4 Performance Data MacDonald Douglas DC-10

In similar manner to the Linjeflyg Airline, the SAS Airline Operations Manual contains information to correct take-off performance for contaminated runway conditions including changes in friction. An extract from the manual provides an indication of the effect of these contaminants on the performance for the DC-10;

1. SUMMARY OF ADDITIONAL CORRECTIONS

(not already included in the diagram overleaf)

Correction for:		Correction on AVAILABLE RW-LENGTH (= physical RW-length)	Correction on TOW vs CLIMB REQ.
QNH	above 1013 mb	+2 m/mb	no corr.
	below 1013 mb	– 10 m/mb	– 300 kg/mb
Frost or ice on underside of wing tanks		– 50 m	– 3000 kg
Braking action	TURB. + FAN reversing AVAILABLE on All engines	– 110 m/0.01 μ below 0.30 If μ not available: – 550 m if MEDIUM to POOR – 1100 m if POOR	
	TURBINE reversing INOPERATIVE on one or more engines	– 120 m/0.01 μ below 0.30 If μ not available: – 600 m if MEDIUM to POOR – 1200 m if POOR	
	ONE TURB. + FAN reversing INOPERATIVE	– 130 m/0.01 μ below 0.30 If μ not available: – 650 m if MEDIUM to POOR – 1300 m if POOR	
Standing water, slush, snow.		Decrease in accordance with § 2 below.	
Anti-skid inoperative		– 1300 m. However, do not exceed a TOW of 226.8 t.	
One wheel brake assembly inoperative		– 410 m At TAILWIND takeoffs do not exceed a TOW of 251.7 t – 1t/kt tailwind.	
Engine failure lights inoperative.		– 130 m	

2. CORRECTIONS FOR STANDING WATER, SLUSH AND SNOW

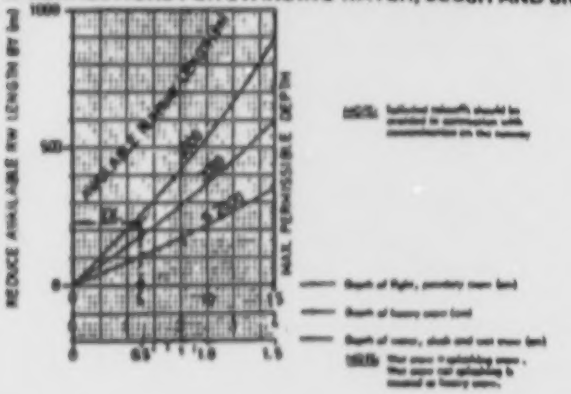
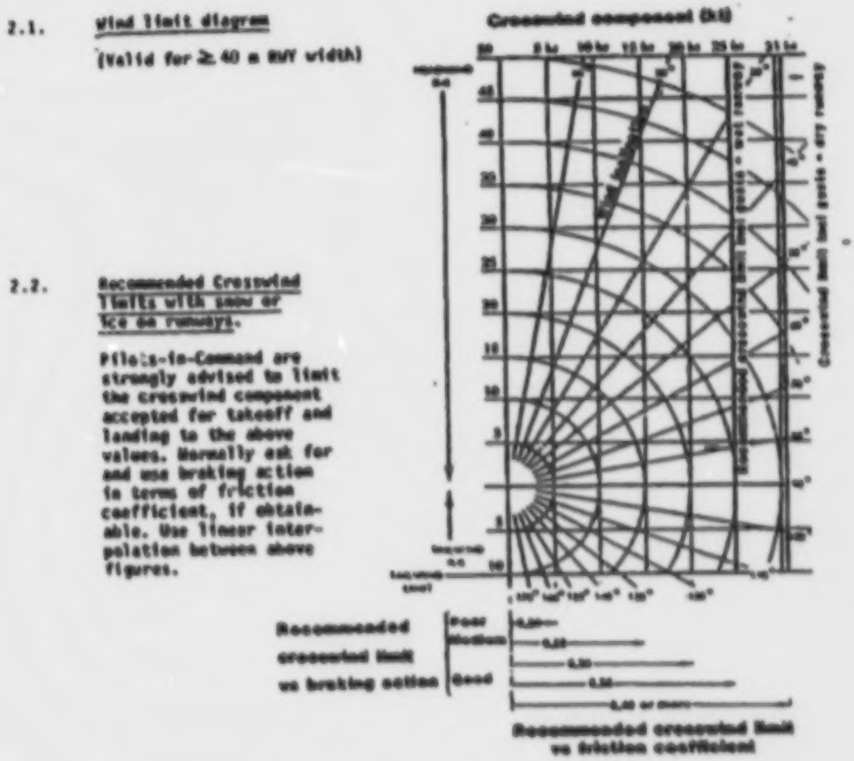


Figure 4.23 Performance Correction Graphs for Contaminated Runways Extracted from the SAS Operating Manual for the DC-10

Source: Ref. 18A, Page 6.3/2

From this example, if reverse thrust is not available and the runway conditions are $\mu = 0.25$ with 8 mm of slush, the runway length required would be increased by 890 meters compared to a required runway length of 3000 meters under dry conditions.

Also included in the SAS DC-10 Operations Manual is the chart on crosswind limits vs μ conditions shown in Figure 4.24.



2.1. Wind limit diagram

(Valid for ≥ 40 m RWY width)

2.2. Recommended Crosswind limits with snow or ice on runways.

Pilots-in-Command are strongly advised to limit the crosswind component accepted for takeoff and landing to the above values. Normally ask for and use braking action in terms of friction coefficient, if obtainable. Use linear interpolation between above figures.

Crosswind component (kt)
Recommended crosswind limit vs braking action
Poor
Medium
Good
Recommended crosswind limit vs friction coefficient

Figure 4.24 Maximum Crosswind Component vs Runway Friction Extracted from the SAS Operating Manual for the DC-10

Source: Ref. 18A, Page 2.4.3

4.4.5 Performance Data British Aerospace BA-146

Ref. 24A, Appendix 3 to the Dan Air BA 146-100 AFM as provided by BA provides for the take-off performance corrections as a function of the extent of runway contamination. The decrease in performance based on the AFM information takes into consideration the increase in drag due to resistance of the undercarriage and the result of impingement of the contaminate. It does not make allowance for the effect of engine failure during take-off in conjunction with contaminant drag; this is consistent with the CAA policy on the probability of both events occurring at the same time. In determining the performance degradation, a runway is considered contaminated when water, slush or snow exceeds 3 mm in depth. The following specific gravities of the contaminant are used: slush SG = 0.85, wet snow SG - 0.4 and dry snow SG = 0.20. Reverse thrust is not installed on the BA 146 and is considered to be not required. The effect on the ratio of contaminated to dry runway TOD shown on the chart for a given indicated contaminant depth is based on a contaminant depth 1.5 times greater than the value on the chart. The BA take-off distances are based on a 15 feet screen height for contaminated runways.

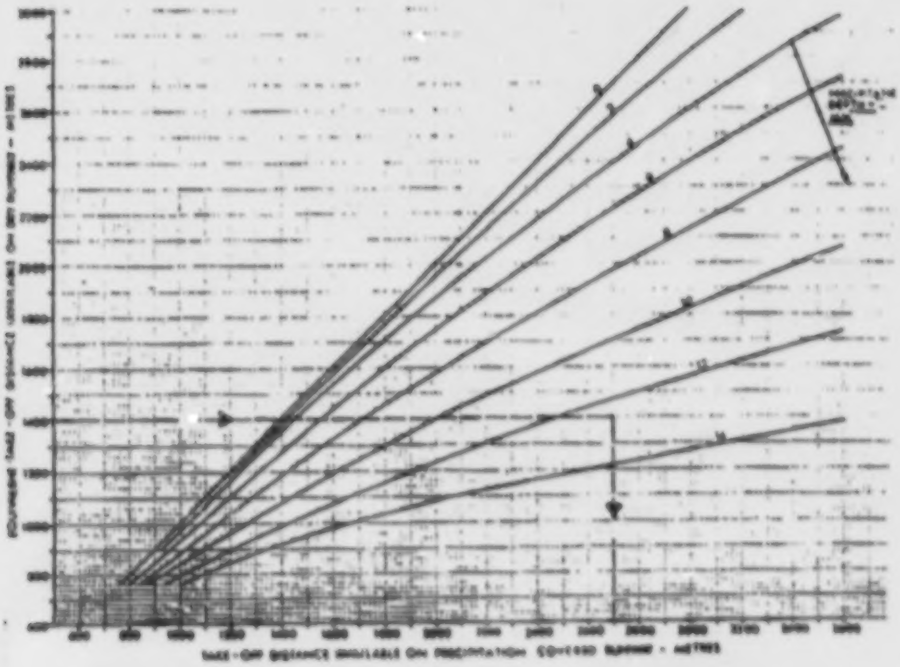


Figure 4.25 Take-off Performance Correction for the BA-146 (all engines operating) on Precipitation Covered Runways

Source: Document No. BAe 3.2, Dec. 83, Fig. 1

The graph indicates that for a runway length required under dry conditions of 2100 meters, with 8 mm of contaminated a runway length of 2930 meters would be required, all other parameters being equal.

4.4.6 Performance Data Douglas DC-8

In Ref. 4, an analysis of the Douglas DC-8 operating in slush conditions ranging in depth between 1/2 to 1 1/2 inches gave the results shown in Figure 4.26.

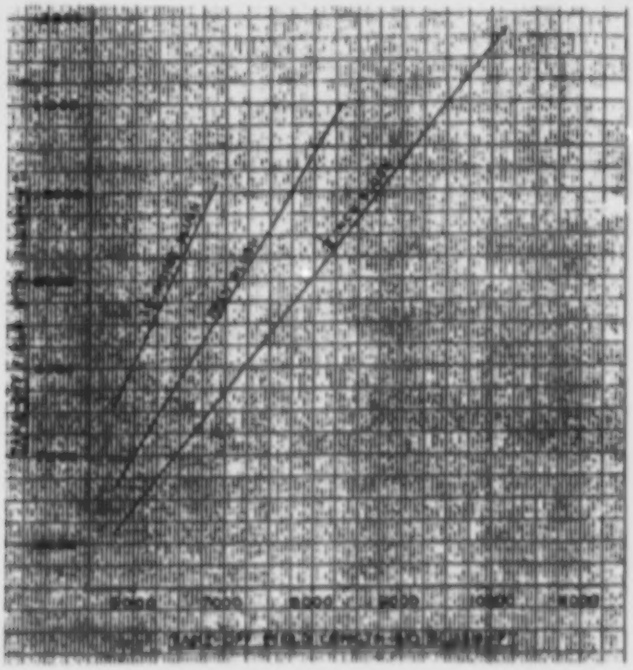


Figure 4.26 Take-off Field Length Required With and Without Slush for a DC-8 Aeroplane

For example, the field length required for a take-off from a runway contaminated with 1/2 in. slush would be 10,600 feet, compared to a field length of 9,000 feet for a dry runway.

It should be noted that this analysis is based only the effect of μ and undercarriage displacement drag and does not include impingement drag.

4.3.7 Summary

The performance data on wet and contaminated runways given in the sections above clearly indicate that runway conditions significantly affect both the accelerate-stop and take-off distances for the B747, A320, F-28, BA146 and DC10.

Comparison of the effects of particular types of contamination on the performance of different aircraft is difficult because of the different methods used for describing and measuring runway condition, as discussed in Section 6. For example, the SAS DC10 operations manual makes no adjustment to the runway length required for runway friction values until μ falls below 0.3. However, the Linjerflyg operating manual for the F-28 indicates that at $\mu = 0.3$ the ATOW must be reduced by 4,000 kg, 12% of the MTOW, which is equivalent to about a 30% increase in ASD. Similarly, the B747 simulator tests indicate that a $\mu = 0.3$ would increase the ASD by 18% over the ASD on a dry runway. In the comparisons of the effect of runway conditions a descriptive value of friction is used, good, medium or poor and, if a μ value is required, it is estimated based on the information given in the manual.

Table 4.7 gives approximate values of the ratio of contaminated to dry values of ASD and TOD for various typical runway conditions. The ratios for each type of contaminant are fairly similar for the different aircraft types, especially for the B747 and A320. Differences between the ratios could be due as much to differences in classifying runway condition when deriving the data, as actual differences in aircraft performance, especially for the DC10 and F-28. The effect of slush, snow and water on TOD is fairly similar between the aircraft types, but the effect of wet, compact snow and ice varies greatly; TOD increases for the B747, but decreases for the A320.

The above data on take-off performance, in conjunction with the frequency of the various runway conditions, is used to estimate the effect on the risk of take-off accidents and incidents in Section 5.

Table 4.7 Ratio of Contaminated to Dry Values of ASD and TOD for Various Typical Runway Conditions

Runway Condition	Friction	Type	Ratio Contaminated / Dry				
			B747[1]	A320[2]	F-28[3]	DC10[4]	BA146
Wet	good-med.	ASD	1.18	1.15	1.11	-	-
		TOD	1.02	0.99	-	-	1.00
Water (6 mm 1/4")	good-med.	ASD	1.70	1.82	1.43	-	-
		TOD	1.06	1.02	-	-	1.11
Slush (8 mm 1/3")	med.-poor	ASD	1.51	1.67	1.64	1.48	-
		TOD	1.12	1.14	-	-	1.19
Compact Snow	med.-poor	ASD	1.43	1.46	-	1.28	-
		TOD	1.05	0.92	-	-	1.00
Loose dry snow (20 mm 3/4")	med.-poor	ASD	1.46	1.65	1.50	1.32	-
		TOD	1.13	1.15	-	-	1.10
Ice	poor	ASD	2.07	-	3.35	1.76	-
		TOD	1.04	0.92	-	-	1.00

Notes:

1. Aircraft-runway $\mu = 0.1$ for ice, 0.2 for slush, loose and compact snow, and 0.3 for water and wet conditions for B747.
2. Friction values for A320 implicit when type of contamination is given.
3. Braking coefficient for F-28 assumed to be: good 0.5, good-medium 0.4, medium-poor 0.3 and poor 0.2 based on range of values in Figure 4.21 and table in Figure 4.22.
4. Distance corrections for DC10 without reverse thrust.

5. RISK ANALYSIS

5.1 Introduction

Aircraft take-off performance depends on a large number of factors, such as runway length, grade and condition, wind, temperature, pressure altitude, take-off weight, type and time of critical event, etc., many of which vary considerably from one take-off to the next. Aviation regulations and operator care attempt to ensure that combinations of these factors that could lead to a take-off accident occur very infrequently. Runway contamination can significantly effect aircraft take-off performance, even without the occurrence of a critical event, but its effect on performance is not included in the current Canadian regulations. The frequency of runway contamination and other adverse factors in Canada is discussed in this section and the current margin of safety on take-off and the accident risk for particular aircraft and airports is calculated.

5.1.1 Margin of Safety on Take-off

The margin of safety on take-off can be thought of as the difference between the runway length available and the runway length required for an aborted or continued take-off, given a critical event occurs at V_1, and actual take-off weight, runway length, grade and conditions, air density and wind conditions. The margin can be positive or negative; by regulation on a dry runway it should be positive. In Canada and the U.S.A. there are no regulations requiring the factoring of dry runway take-off distance when the runway is wet or contaminated; thus, under these runway conditions, the margin of safety can be negative.

The margin of safety includes all known conditions for the take-off, including the runway condition, and allows for a critical event (such as engine failure) to occur at the time which will result in the longest accelerate-stop and take-off distances, i.e., at V_1 speed. A large margin of safety will contribute to the prevention of accidents in situations where a critical event occurs near V_1 and other conditions, malfunctions or errors occur which affect the aborted or continued take-off. These could include:

- malfunction of brakes, tires or other equipment,
- excessive pilot response time,
- delays in applying braking devices or other human factors.

Malfunction of brakes, tires, etc. and human factors cannot be foreseen before a departure. They are random events which occur with some probability after the critical event. As the probability of the malfunction/error is low and the consequences are usually not catastrophic, no additional margin of safety is required by regulation for these events.

The margin of safety should include the effect of runway condition because runway condition is known before a departure and it is therefore possible to estimate its effect on performance and include it in the calculation of maximum take-off weight, speeds and take-off distances.

When the aircraft take-off weight is restricted by the aircraft's certified maximum take-off (MTOW) rather than the runway length available, the aircraft can often depart with some margin of safety. Table 5.1 gives the approximate required runway lengths for a number of aircraft at MTOW and the actual runway lengths at 28 Canadian airports. The required runway lengths are for zero wind conditions and runway grade, at sea level and standard ISA temperature (15°C), and will vary depending on the values of these parameters and aircraft load factors. Take-off distances increase by approximately 6% with every 1000 feet increase in altitude and 6% with every 10°C increase in temperature (based on results in Appendix E). The required runway varies considerably between models of the same aircraft type and this greatly affects the margin of safety available. At many airports the runway length is considerably more than the runway length required by many of the jet aircraft using the airport. Table 5.1 also shows the variation in required runway lengths for different models of the same aircraft type and the margin of safety is very dependent on the model as well as the aircraft type.

Actual (or dispatch) take-off weights, TOW, are usually less than MTOW, thus reducing the distance required for take-off and increasing the margin of safety. The variation in take-off weight for aircraft in Canada and its effect on the margin of safety is discussed in Section 5.3.

Table 5.1 Runway Lengths Required for Take-off at MTOW and Runway Lengths Available at 28 Canadian Airports*

Aircraft Type	Required Runway (feet)	Airport	Rwy Length Available (feet)	Most Common Aircraft Using Airport			
Concorde	11155	Calgary Int.	12675	B737	B727	DC9	B767
B747-100	10040	Montreal Mirb.	12000	B747	L101	DC8	DC10
-200	10340	Toronto Int.	11050	B727	B737	DC9	B767
DC10-10	10500	Montreal Dorv.	11000	B737	B727	DC9	FA28
-30	10400	Vancouver Int.	11000	B737	B727	DC9	DC10
-40	10250	Winnipeg Int.	11000	B737	B727	DC9	A748
DC8-63	10420	Edmonton Int.	11000	B737	DC9	B727	B767
L1011-2	8100	Gander Int.	10500	L101	B737	B727	
-5	9330	Vald'Or	10000	A748	B737	DC9	FA28
B767-200	6500#	Ottawa Int.	9700	B737	B727	DC9	A748
-300	8900#	Quebec City	9000	DC9	FA28	B737	B727
B727-100	8208	Halifax Int.	8800	B737	B727	DC9	B767
-200	10420	St. John's	8500	B737	B727	DC9	
B737-100	8200	Saskatoon	8300	DC9	B737	FA28	B727
-200	7530	Regina	7900	DC9	B737	FA28	B727
-200A	8880	Windsor	7900	DC9	B737		
-300	6650#	Yellowknife	7500	B737	B27	C550	
DC9-30	7000	Prince George	7400	B737	C550	C500	
-50	8040	Saint John	7000	DC9	B737		
A310	8550	Victoria Int.	7000	C500	C550	B737	DC9
BAC111-500	7900	Fort St. John	6900	B737	FA28		
A300 B4	6050	Sept-Iles	6572	B737	FA28	DC9	
FA 28	5200^	Thunder Bay	6200	B737	DC9	A748	
CL600	4300	Kamloops	6000	B737	C550	C500	
LearJet 55	4300	Fredericton	6000	DC9	B737		
BAe 146-100	3530^	Sault S. Marie	6000	B737	FA28		
HS 748-2B	2650^	Edmonton Mun.	5868	B737	C550	FA28	C500
		Kelowna	5350	B737	C550	C500	

* Required runway for MTOW, sea level, standard atmospheric conditions, still air and zero runway slope given in ICAO Aerodrome Design Manual, Part 1, Runways (1984). Doc. 9157-AN/901; runway lengths available for longest runway, excluding stopway and clearway.

# Distances given in Aviation Week & Space and Technology, March 1990.

^ Distances given in Commuter Air, September 1982.

Determination of the margin of safety under current regulations allows a better understanding of why so few take-off accidents occur. The margins of safety for particular aircraft at six Canadian airports are developed in Section 5.6.

5.1.2 Accident/Incident Risk

In Phase I of the project, only take-off accidents/incidents where the aircraft runs off the end of the runway in an aborted take-off, or hits obstacles at the end of the runway on a continued take-off, are considered in the risk model. In the latter case, an accident/incident is assumed to occur if the aircraft fails to clear the 35 foot screen height at the end of the runway.

A take-off accident/incident is assumed to be preceded by an occurrence of some type of critical event on the take-off run which necessitates a decision by the pilot on whether to abort or continue the take-off. The outcome of this take-off is dependent on the margin of safety available for the take-off, the type and timing of the critical event, delays in aborting take-off and other malfunctions or human factors. The effect of the type and time of the critical event and pilot delay in aborting take-off will be considered, but not the effect of any malfunction of the brakes, tires or other equipment.

In addition to these factors, the accelerate-stop distance in an aborted take-off is dependent on whether reverse thrust was used, especially on contaminated runways. Current Canadian and U.S. regulations do allow for reverse thrust in the calculation of required take-off distance if controllability and reliability requirements are met. However, in practise, in the U.S. no aircraft have been given operational approval for including reverse thrust in the calculations and in Canada only the BAC 111 has been given approval. Reverse thrust may be used at the pilot's discretion to reduce the accelerate-stop distance and its effect is included in the risk model (Section 5.7 and Appendix E-8).

The factors affecting take-off performance and their use in the risk model are shown in Figure 5.1. The primary factors affecting take-off weight and distance are given across the top of the figure. The occurrence of a critical event on the take-off run leads to the pilot's decision on whether to abort

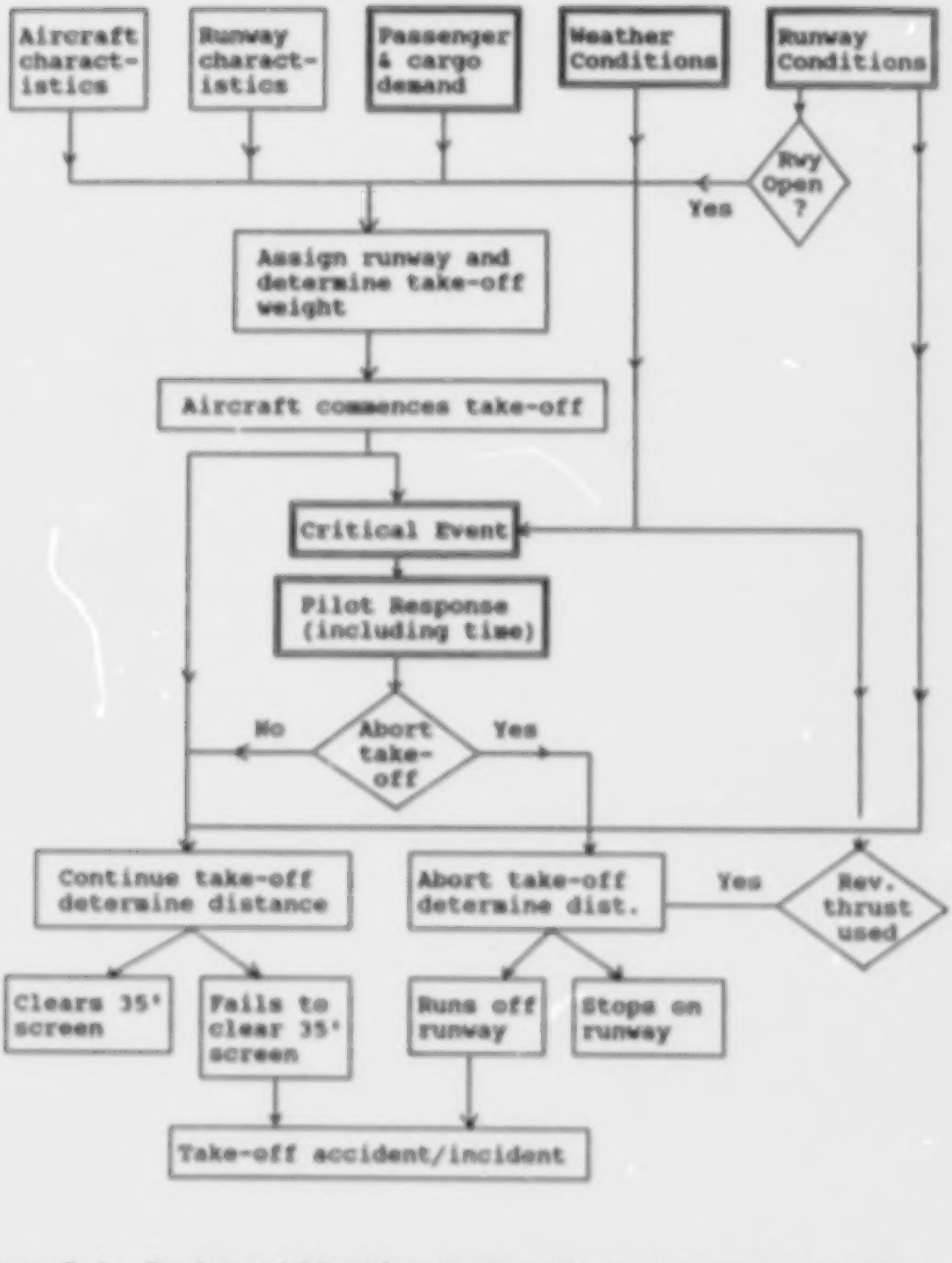

Aircraft characteristics
Runway characteristics
Passenger & cargo demand
Weather Conditions
Runway Conditions
Rwy Open ?
Yes
Assign runway and determine take-off weight
Aircraft commences take-off
Critical Event
Pilot Response (including time)
No
Abort take-off
Yes
Continue take-off determine distance
Abort take-off determine dist.
Yes
Rev. thrust used
Clears 35' screen
Fails to clear 35' screen
Runs off runway
Stops on runway
Take-off accident/incident

Figure 5.1 Factors Affecting Take-off Performance and Their Use in the Risk Model*

- Doubled lined box indicates factor is variable and the probability of each possible value is used in model or continue the take-off, depending on the aircraft speed. The distance required to stop the aircraft in aborted take-offs is also dependent on the use of reverse thrust and the pilot response time.

An accident/incident will occur if the required take-off distance, or accelerate-stop distance for aborted take-offs, allowing for runway conditions, is greater than the runway length available. The additional distance provided at some airports by stopways and clearways was not considered during this Phase of the project. The overrun distance (the amount by which the required runway distance exceeds the available distance) will be related to the severity of the accident/incident. As the severity of an accident/incident is very dependent on the terrain at the end of the runway, which varies greatly from runway to runway, the overrun distance required is used as a measure of the severity.

The risk of a critical event occurring during the take-off run is discussed in Section 5.2 and the probabilistic model for the occurrence of a critical event used in the risk model is given in Appendix E-7. The frequency of runway contamination at Canadian airports and the depth of contaminants and runway friction values are discussed in Section 5.3. The model used for determining the margin of safety and accident probabilities is discussed in Section 5.4 and Appendix E. Estimates of accident probabilities and the distributions of the overrun distance for particular aircraft types and airports are given in Sections 5.6.

5.1.3 Aircraft and Airports Used in Analysis

The criteria used for choosing aircraft types for use in the risk analysis was that aircraft performance data on contaminated runways must be available, a range of aircraft sizes must be covered and at least one aircraft type must be able to depart from the smaller airports selected for analysis.

Take-off performance data on contaminated runways is not available for the most common jet aircraft types in Canada - the B737, B727 and DC9. Contaminated runway performance data were developed for the B747-100 using the University of Toronto Institute for Aerospace Studies (UTIAS) simulator, and was obtained for the A320 and BA146-100 from appendices to the AFM's. These three aircraft, whose characteristics are summarized in Table 5.2, were used in the risk model. Performance data for dry runways for the three aircraft were obtained from the aircraft flight manuals (AFM).

Table 5.2 Characteristics of Aircraft Selected for Use in Risk Analysis

Characteristic	B747-100	A320	BA146-100
Maximum Take-off Weight (lbs)	730,000	162,000	82,250
Number of Engines	4	2	4
Number of Seats	500	160	96
Take-off distance (ft)*	11,600	10,000	3,700
Wing Height	Low	Low	High

* Approximate take-off distance at maximum take-off weight, sea level, zero grade and wind, dry runway, 15°C.

Six airports were selected for use in the study so that a range of runway lengths and forms of contamination would be covered and preference was given to airports that had a large number of jet aircraft departures for a given runway length. The six runways used in the analysis and some characteristics of those airports are given in Table 5.3.

Table 5.3 Characteristics of Airports Selected for Use in the Risk Analysis

Airport	Runway Length (feet)	Altitude (feet)	Snowfall Hours	Departures (1988)*		
				B747	B737	All Jet
Toronto Int.	11,050	569	594	3557	26005	108967
Calgary Int.	12,675	3,557	785	309	17358	41966
Ottawa Int.	9,700	374	720	5	7885	25504
Halifax Int.	8,800	477	843	7	7638	15293
Edmonton Mun.	5,868	2,200	842	0	5833	9493
Prince George	7,400	2,268	813	0	2154	3546

* Model numbers were not identified

Only six airports were selected as the runway condition data is not on a computerized database and determining the distribution of runway conditions at each airport was a very time consuming task.

5.2 Frequency Of Critical Events On Take-off

The risk, or probability, of a critical event on take-off can be estimated from past data by dividing the number of critical events on take-off by the number of attempted take-offs.

This risk is estimated using the Canadian accident/incident data obtained from TIASB and airport departure data published by Transport Canada. The number of incidents in Canada allows good estimates of the risks of a critical event to be obtained and it was therefore not necessary to rely on estimates from other countries.

The critical events on take-off occurring at Canadian airports are discussed in Section 2.3. As discussed in that section, reporting of particular incidents has been mandatory since 1985, but was not complete prior to 1986. However, since 1986 the reporting has been more reliable and should include close to all incidents where a critical event occurred on the take-off run. Therefore, only incidents reported between 1986 and 1989 are used in calculating the risks. The number of reported critical events during jet aircraft take-offs are given in Table 2.7.

5.2.1 Exposure to Risk

The number of departures of jet aircraft from Canadian airports is given in Table 5.4. Data for 1989 are not yet available and have been estimated assuming a linear increase since 1986.

5.2.2 Risk per Departure

The risk of a critical event on take-off and the standard deviation of the estimated risk, calculated using the frequency of critical events given in Table 2.7 and the number of departures given in Table 5.4, are given in Table 5.5.

Table 5.4 Number of Jet Aircraft Departures from Canadian Airports*

Year	Jet
1986	455,100
1987	452,300
1988	486,900
1989	496,700
Total	1,891,000

* Half of itinerant movements published in "Aircraft Movement Statistics" by Transport Canada, Report No. TP577.

Table 5.5 Risk of Critical Event on Take-off for Jet Aircraft in Canada

Type of Critical Event	Risk per million departures*	
Engine Failure	13.2	(2.6)
Warning Light	7.4	(2.0)
Tire Failure	6.9	(1.9)
Loss of Control	2.6	(1.2)
Other	7.9	(2.0)
Any Critical Event	38.1	(4.5)

* Standard deviation given in brackets based on a Poisson distribution of critical events

In the risk model, critical events are classified into two types, engine failure or other than engine failure. The risks of aborted take-off and continued take-off due to each of these two types of critical events are given in Table 5.6.

The effect of engine failure on the take-off and accelerate-stop distances can be determined from the AFM. However, the effect of other types of critical events depend greatly on the type of event and are difficult to determine. Some fairly common critical events, such as false warning light or tire failure, have negligible effect on take-off and accelerate-stop distances. Therefore, in the risk model it is assumed that critical events other than engine failure have no effect on the take-off and accelerate-stop distances; this assumption will lead to the accidents risks being underestimated.

Table 5.6 Risk of Aborted Take-off and Continuing Take-off after a Critical Event for Jet Aircraft in Canada

Outcome of Event	Risk per million departures for a Given Event:		
	Engine Failure (Col.1)	Other Than Eng. Failure (Col.2)	Any Critical Event (Col.1 + Col.2)
Abort	11.6 (2.5)	13.2 (2.6)	24.9 (3.6)
Continue	1.6 (0.9)	11.6 (2.5)	13.2 (2.6)
Abort or Cont.	13.2 (2.6)	24.8 (3.6)	38.1 (4.5)

* Standard deviation of risk probability given in brackets

The risk of engine failure on the take-off run is dependent on the number of engines on the aircraft; the more engines the greater the risk of engine failure. To determine the risks with different numbers of engines, departure data for each aircraft type in 1988 was used to estimate the percentage of departures by two, three and four engine aircraft. These percentages and the estimated number of departures between 1986 and 1989 are given in Table 5.7. The observed number of engine failures and the calculated risk of engine failure are also given in Table 5.7. The risks are calculated per departure and per engine departure (i.e., departures weighted by number of engines).

Table 5.7 Departures and Engine Failure Risk for 2, 3 and 4 Engine Jet Aircraft - Canada 1986-1989

No. of Engines	% of Deps.	Est. Deps. 1986-89	Engine Fail.	Risk of Eng. Fail. per million:	
				Dep.	Eng.-Dep.
2	93.0	1,759,086	19	10.8	5.4 (1.2)
3	5.7	108,048	3	27.8	9.3 (5.3)
4	1.3	23,865	3	126	31 (18)
Total		1,891,000	25	13.2	6.3 (1.3)

* Standard deviation of risk probability given in brackets

The data indicate that engine failures on the take-off run are far more likely on aircraft with four engines and that the number of engines should be taken into account when determining the risk of engine failure on take-off. Engines on four engine aircraft have a much higher failure rate on take-off per engine-departure than engines on 2 or 3 engine aircraft, but the difference is not statistically significant. Therefore, for the purposes of this study, each engine on all aircraft are assumed to be equally likely to fail and the single engine failure rate of 6.3 failures per million engine-departure is used.

In terms of safety, four engine aircraft are more likely to have an engine failure on take-off, but the proportion of the engine power still available for take-off is greater than on two or three engine aircraft. Thus, engine failures after V_1 speed tend to be less critical on four than on two engine aircraft. The greater chance of engine failure on the four engine aircraft will lead to a greater risk of aborted take-offs and the hazards they entail. This is offset to some extent by lower values of V_1 since the 4 engine aircraft tend to be less constrained by the engine-out continued takeoff.

Critical events on the take-off run pose the greatest threat to safety when they occur near the decision speed, V_1. The risk of an accident changes depending on the speed at which the critical event occurs. To determine the accident risk it is therefore necessary to estimate the probability of a critical event occurring at a given speed. This is considered in Appendix E-7.

5.3 Take-off Weights

Aircraft take-off weights greatly affect both the take-off and accelerate-stop distances. The distribution of take-off weights for common aircraft types at airports in Canada and the effect of these take-off weights on the margin of safety was estimated.

The take-off weights and margin of safety could be found directly from air carrier dispatch data, but this data could not be obtained from the carriers. It was therefore necessary to estimate take-off weights and the margin of safety using available data from various sources.

Take-off weights of aircraft departing from airports in Canada were determined using data collected by the Aviation Statistics Branch of Statistics Canada (using Daily Airport Activity Report Statements 2 and 6). The data are collected from the carriers and include for each flight the available weight capacity for cargo and passengers and the actual cargo weight and number of passengers onboard. An average passenger weight (including luggage) of 200 lbs (91 kg) was assumed when calculating the weight.

The actual take-off weight could not be determined for each flight as the fuel load was unknown. However, it was possible to determine the amount the actual dispatch weight, TOW, was under the allowed (or runway restricted) take-off weight, ATOW. This amount under ATOW was converted to a percentage by dividing by the maximum certified take-off weight (MTOW). Use of percentages allows easy comparison of the values between aircraft types. The method used to calculate these percentages under ATOW is fully described in Appendix E-5.

The percentage under ATOW varies between 0% and 25% and the frequency distribution roughly forms a bell shaped (or normal) curve as shown in Figures 5.2(a) for departures from Ottawa and 5.2(b) for departures from Toronto. Mean values of the

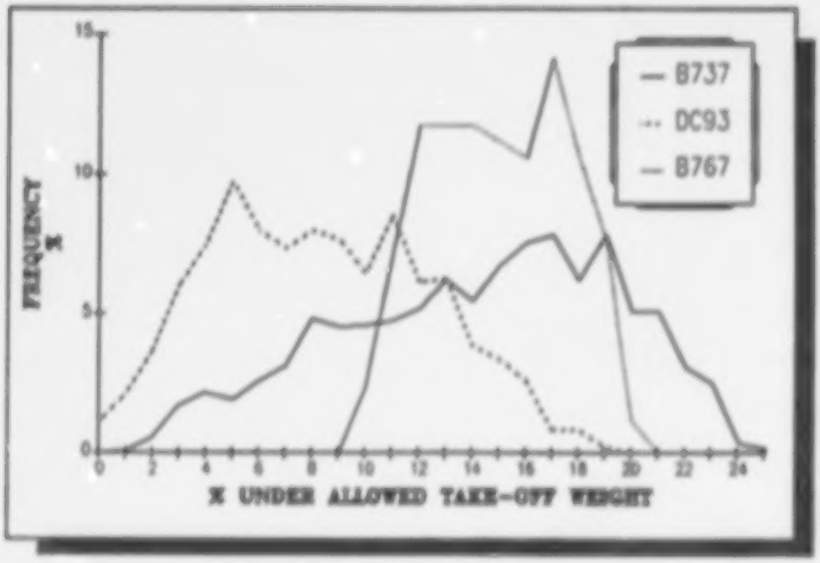


Figure 5.2(a) Frequency Distribution of Percentage under ATOW for Various Aircraft at Ottawa Airport

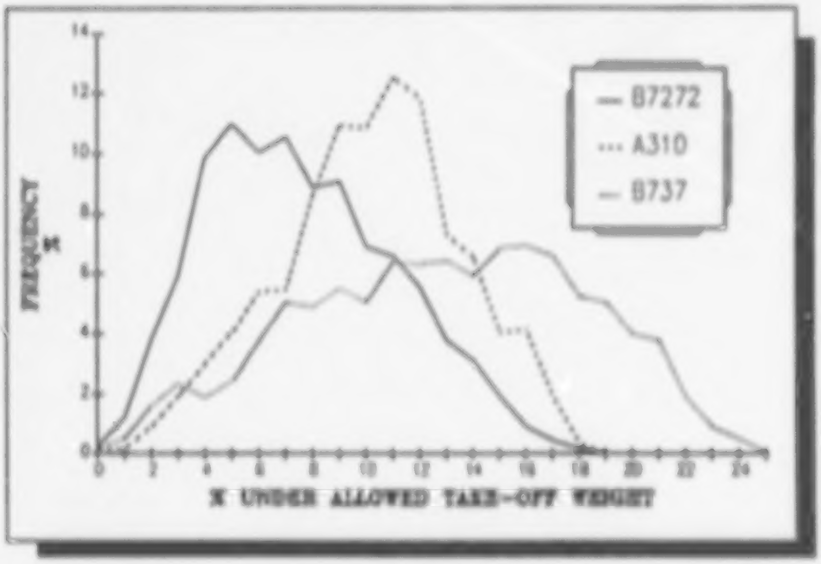


Figure 5.2(b) Frequency Distribution of Percentage under ATOW for Various Aircraft at Toronto Airport

percentage under ATOW are in the range of 7% to 15% for most aircraft at most airports. The average percent under ATOW at a number of Canadian airports is given in Table 5.8. The mean percentage under ATOW for a particular aircraft does not vary greatly between airports, but the variation between aircraft types is considerable.

Table 5.8 Mean Percentage Under ATOW for Aircraft at Six Canadian Airports in 1988-1989*

Airport	% Under ATOW for Aircraft:							
	B737	B727	B767	B747	DC9	DC8	DC10	A310
Ottawa	14.7	9.4	15.4	-	8.8	19.0	-	14.1
Toronto	13.4	8.1	12.1	17.7	8.2	15.5	8.7	10.7
Calgary	12.9	9.1	13.3	19.8	7.8	19.2	8.5	11.6
Halifax	13.3	8.3	11.3	-	8.7	21.0	6.2	-
Edmonton Municipal	14.7	-	-	-	-	-	-	-
Prince George	15.3	-	-	-	-	-	-	-

* "-" indicates that aircraft had less than 10 departures from that airport during 12 months in 1988-1989; A320 and BA146 had no departures in Canada during that period.

The take-off weight of a particular aircraft type at a particular airports varies considerably by time of day and year. Table 5.9 gives the mean values of the percentage under ATOW for a number of aircraft and airports for different times of the day. During the evening peak periods the aircraft are usually more fully loaded (values are less), but during the morning peak periods the trend towards higher load levels is not as consistent.

Table 5.9 Variation in Percentage Under ATOW with Time of Day

Airport/ Aircraft	Percentage Under ATOW for Times:								
	6-8am	8-10	10-12	12-2pm	2-4	4-6	6-8	8-10	10-12
Toronto									
B737	15.0	15.0	12.7	16.0	13.2	10.8	12.2	13.3	14.8
B727	9.3	9.1	7.6	9.2	10.1	7.7	8.3	12.8	14.1
B747	26.2	18.8	20.4	26.1	23.5	19.8	11.7	15.6	16.9
A310	11.6	10.3	8.7	10.8	12.5	9.9	9.6	9.4	13.0
Ottawa									
B727	9.3	9.1	7.6	9.2	10.1	7.7	8.3	12.8	14.1
B767	15.1	15.4	16.9	15.4	15.4	15.2	14.1	15.4	15.4
Prince George									
B737	17.6	18.3	11.6	16.6	6.0	10.8	12.2	17.8	15.3

Monthly variations in the percentage under ATOW can also be quite significant, differences of over 1% from the average value were found for many aircraft types and airports. Take-off weights tend to be closer to the ATOW in the summer months than during the winter months. This is due in part to the higher ATOW's during the winter months as required runway lengths are less at cold temperatures.

Most aircraft take-off at between 5% and 15% under the ATOW of the aircraft. The effect of take-off weight on the required take-off distance varies from aircraft to aircraft, but when expressed as a percentage reduction in the required distances, the effects are fairly similar. The percentage under ATOW is always greater than or equal to the percentage under MTOW as ATOW is less than or equal to MTOW. In Appendix E a method is given for estimating the effect of percentage under MTOW on required take-off distance for the B747-100, A320 and BA146 and the estimated values are given in Table 5.10. Typically, a margin of safety of between 10% and 30% of the runway length is available due to aircraft taking off at under ATOW.

Table 5.10 Approximate Change in Required Take-off Distance with Percentage Under MTOW for B747-100, A320 and BA146

Percentage Under MTOW	% Change in Required Take-off Dist. B747-100	A320	BA146
5%	-13%	-10%	-11%
10%	-24%	-18%	-20%
15%	-34%	-26%	-28%
20%	-42%	-34%	-36%

5.4 Runway Conditions

Canada, with its extremes in climate, experiences a wide range of runway conditions at its airports. In winter, loose or drifting snow, ice and slush are relatively common, while in summer, thunder storms and heavy rain showers can result in standing water on the runways. The frequency of occurrence of wet and contaminated runways has not been well documented and its effect on aviation safety is not clear.

5.4.1 Winter Runway Conditions

Transport Canada (TC) has a reporting mechanism in place for recording runway conditions during the colder months of the year when snow fall is likely (usually November to March). A runway condition report, given in Appendix F, is filed whenever the runway conditions change significantly. Thus, the time from one report to the next is the time when a report is applicable. The percentage of the runway which is bare and dry, bare and wet, snow covered (various categories) and ice or frost covered is recorded on the report for each runway. In addition, the results of a runway friction measurement is recorded whenever a measurement is taken. The reports therefore provide a good data source on which to estimate the frequency of wet and contaminated runways conditions during the period November to March.

Runway conditions reports were obtained for the last three years from Ottawa, Halifax, Edmonton and Calgary International airports and from Prince George airport. Reports for Edmonton Municipal airport were not available and runway conditions at Edmonton International were used in their place. Reports were not available from Toronto International and the risk model uses Ottawa data instead. It is recognized that Ottawa conditions are more likely to be worse than Toronto because of more extreme climate, and that therefore the substitution creates a "worst case" for Toronto.

Runway conditions sometimes vary along the runway, especially when the runway is contaminated. As the number of combinations of different runway conditions is large, it is not easy to give a simple picture of the runway condition. An overall view of the runway conditions can be obtained by considering the average percentage of time a small section (i.e. randomly chosen area or segment) of the runway is in each condition. Table 5.11 gives these percentages for the main runway at each of the five airports. The frequency of runway conditions are calculated using only data for the time period from 6 am to 11 pm each day as very few take-offs occur outside this period. A more complete picture of the runway conditions is given in Appendix F.

Table 5.11 Average Percentage of Time a Section of the Runway is in Each Condition for five Airports#

(a) OTTAWA

Condition	Nov	Dec	Jan	Feb	Mar
Rwy closed	1.1	0.7	1.7	1.8	0.4
Bare - dry	63.2	59.3	62.4	73.1	75.4
Bare - wet	25.6	11.4	9.0	6.5	14.7
Snow - cover	2.8	11.0	9.4	7.7	2.6
Snow - drift	0.0	0.8	0.5	0.9	0.2
Snow - patch	1.0	2.9	4.9	3.6	0.8
Ice - cover	3.8	12.0	9.3	5.7	5.1
Snow over ice	0.0	0.0	0.0	0.0	0.0
Slush cover	2.5	1.4	0.9	0.6	0.7
Frost	0.1	0.5	1.9	0.1	0.1
Total hours*	1960	2125	2123	1935	2110

Table 5.11 Average Percentage of Time a Section of the Runway is in Each Condition for five Airports#
(Continued)

(b) HALIFAX

Condition	Nov	Dec	Jan	Feb	Mar
Bare - dry	58.9	51.5	37.3	34.4	56.3
Bare - wet	26.3	15.4	22.8	8.6	15.3
Snow - loose	5.3	10.7	15.2	20.9	8.3
Snow - drift	2.1	4.2	2.5	5.1	1.1
Snow - compt	0.6	1.8	2.3	6.1	0.6
Ice - patch	4.9	11.7	14.1	20.0	13.1
Slush cover	1.9	3.2	2.9	2.7	5.5
Frost	0.0	1.4	3.0	2.2	0.0
Total hours*	1330	1154	1109	651	898

(c) CALGARY

Condition	Nov	Dec	Jan	Feb	Mar
Bare - dry	91.0	81.8	88.0	84.9	89.3
Bare - wet	4.0	4.6	1.8	3.2	5.5
Snow - loose	1.9	9.1	5.4	7.8	2.4
Snow - drift	0.2	0.2	1.0	0.1	0.0
Snow - compt	0.8	0.4	0.5	0.9	0.7
Ice - patch	1.9	2.9	1.6	1.2	1.7
Slush cover	0.2	0.5	0.4	0.7	0.2
Frost	0.0	0.5	1.3	1.2	0.1
Total hours*	1551	1575	1022	969	1326

(d) PRINCE GEORGE

Condition	Nov	Dec	Jan	Feb	Mar
Bare - dry	41.0	54.7	42.0	50.2	63.8
Bare - wet	39.7	17.0	10.5	17.5	23.4
Snow - loose	11.9	17.7	26.7	18.3	8.2
Snow - drift	1.7	2.3	2.8	0.2	0.3
Snow - compt	0.2	0.4	1.0	0.6	0.2
Ice - patch	4.2	6.7	13.5	11.9	2.8
Slush cover	1.2	0.7	1.2	1.0	1.3
Frost	0.1	0.5	2.5	0.3	0.0
Total hours*	1514	1580	1582	1645	1568

Table 5.11 Average Percentage of Time a Section of the Runway is in Each Condition for five Airports#
(Continued)

(e) EDMONTON

Condition	Nov	Dec	Jan	Feb	Mar
Bare - dry	90.7	65.1	73.3	73.1	87.6
Bare - wet	3.0	4.7	3.1	6.4	1.6
Snow - loose	2.7	9.7	9.5	8.6	3.9
Snow - drift	0.0	0.0	0.0	0.0	0.5
Snow - compt	2.0	2.9	1.5	2.3	0.9
Ice - patch	1.6	17.0	9.2	7.4	5.4
Slush cover	0.0	0.0	0.7	0.0	0.0
Frost	0.0	0.5	2.6	2.2	0.0
Total hours*	1037	1037	1502	1431	765

Probability that any given patch of runway has the following runway condition.
* Number of hours on which percentages are based.

The main runway at the five airports is wet or contaminated, on average, a third of the time during the colder months. At Calgary and Edmonton, the proportion drops to 10% to 30% of the time, while at Prince George and Halifax the proportion rises to 40% to 65% of the time. Snow is the most frequent form of contaminant during December to February (10% to 30%), but the frequency of snow contamination drops by a third of this during November and March. Ice on the runway is relatively common at four of the airports (not Calgary), but fluctuates greatly with month. The chance of ice on a section of the runway varies from 2% to 20% at these airports over the five months. Slush and frost on runways are fairly uncommon, each occurring less than 3% of the time at these airports during November to March.

The effect of these levels of runway contamination on aircraft performance was estimated using performance data given in Section 4.3. The ratio of the contaminated to dry value of the ASD and TOD was calculated for each runway condition reports using the ratios for typical conditions given in Table 4.7 (see Appendix E for details) and the frequency distribution of the ratio was estimated. An example of the distribution of the ratios for departures of the B747 aircraft at Ottawa airport over the months November to March is shown in Figure 5.3. The figure shows that, for the B747 at Ottawa, the runway conditions cause a 50% increase in the ASD relatively often, but there are very few times when the effect is greater than 50%. The effect of runway conditions on TOD is much less and is rarely greater than 10% of the runway.

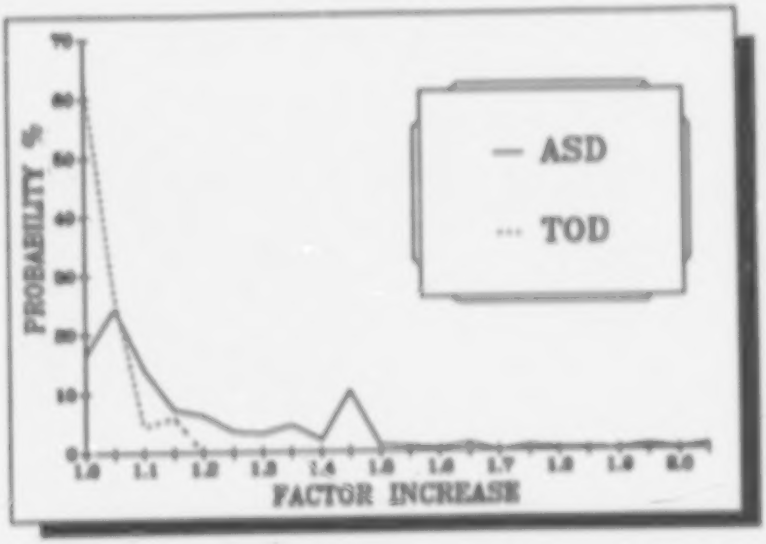


Figure 5.3 Frequency Distribution of the Ratio of Contaminated to dry Values of ASD and TOD for Departures of B747 at Ottawa

Given a particular type of runway condition, e.g., loose snow, the depth of contaminant and effect on the braking performance of the aircraft can vary considerably. The TC runway condition reports were analyzed to determine the distribution of the depth of contaminant and the runway friction measured using a ground vehicle. Figure 5.4 shows the frequency distribution of the reported depth of contaminant for sections of the runway with the three types of snow cover. It is assumed that if no depth is given only a "trace" is present. The mean depths of snow (assuming depth of 0.06 inches (1.5 mm) when "trace" was given) were found to be:

Loose snow   Mean depth = 0.6 inches (15 mm)
Snow Drift   Mean depth = 1.5 inches (38 mm)
Slush   Mean depth = 0.3 inches (8 mm)

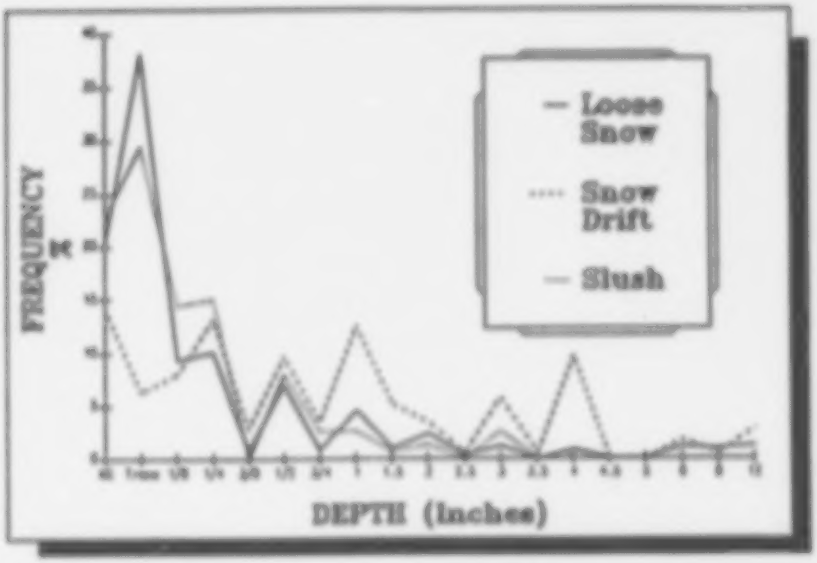


Figure 5.4 Frequency Distribution of the Reported Depth of Contaminant for Loose Snow, Snow Drift and Slush Contamination*

- Distribution not weighted by time the report is applicable and does not give probability of depth of contaminant at any time; NG denotes depth value not given.

The runway friction coefficient, μ, was measured using one of a number of types of devices mounted in a ground vehicle (discussed in Section 3.4) and are recorded on the runway condition report. The devices used at the five airports during the winter periods for which data was analyzed were:

Ottawa	Tapley meter
Halifax	James Brake Indicator (JBI)
Calgary	James Brake Indicator (JBI)
Edmonton Int.	Tapley meter
Prince George	James Brake Indicator (JBI) 1987/88 & 1988/89, Electronic decelometer 1989/90

The number of measurements taken varies from airport to airport, but are taken more frequently when the runway conditions are poor. Friction measurements are taken over the full length of the runway and can therefore include the effects of more than one type of runway contamination. In the analysis, friction measurements were only associated with a particular runway condition when more than half the runway was in that condition. The frequency distribution of the friction measurements for each of the runway conditions are given in Figure 5.5. The distributions for each airport are given in Appendix F.

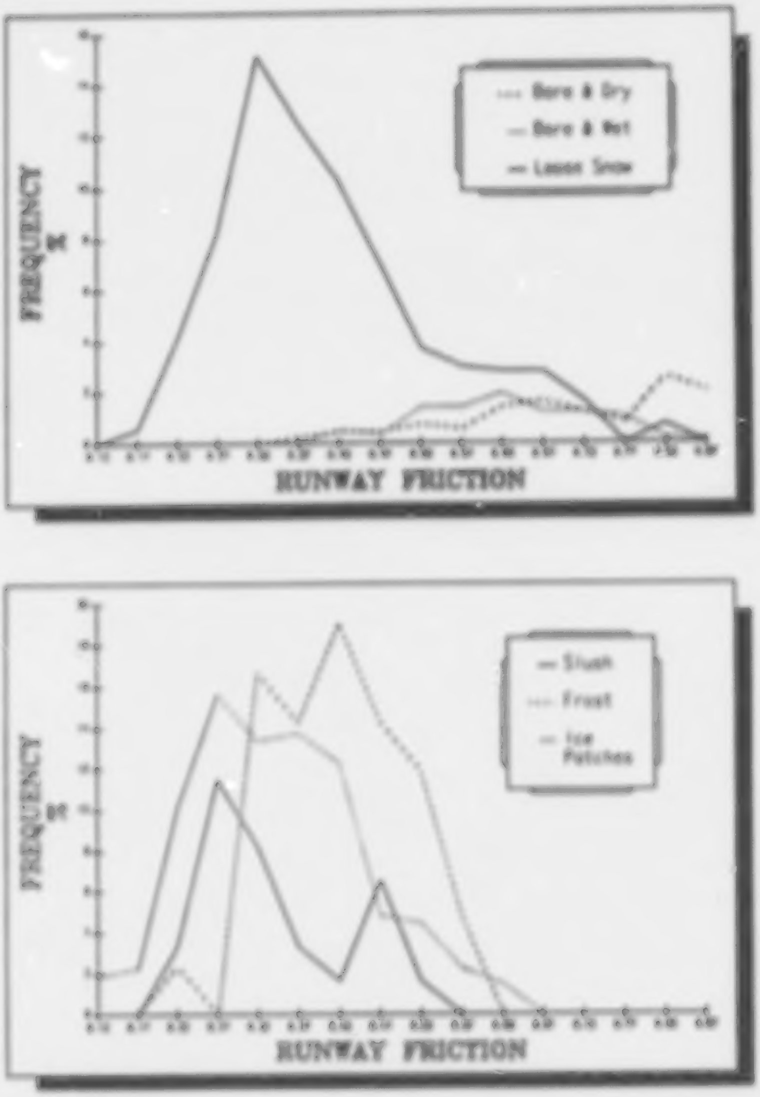


Figure 5.5 Frequency Distribution of the Measured Runway Friction Given the Type of Runway Contamination*

- * Friction values often not given when runway was dry or wet; distribution not weighted by time the report is applicable and does not give probability of a friction value at any time

When the runway was bare and dry or bare and wet runways, a friction measurement was recorded on only 10% of the reports. For loose snow, frost and ice patches friction measurements were made for about 80% of the reports, but measurements were only made for 40% of reports for slushy runway conditions. The distributions in Figure 5.5 show that ground vehicle runway friction values of less than 0.3 occur often when the runway is contaminated with snow or ice.

The measured friction values vary considerably for the same runway condition, even on bare and dry runways. This is partly due to the known temperature sensitivity of the Tapley measuring device (Ref 55) and could also be due to the different measuring devices and due to the variation in the conditions when more than 50% of the runway is in a given runway condition. As discussed in Section 3.2, the variation could also be due to test procedures not being standardized across Canada and different vehicles, drivers, etc.

The mean values of the ground vehicle friction measurements when more than half the runway was in each condition are given in Table 5.12. These friction values represent fairly typical values when most of the runway is in a particular condition, but do not give the friction value for a particular type of contamination. For example, when the runway was classified as 100% ice patches, the mean friction value was 0.32. The typical range of values of μ for each condition measured by various ground vehicles in tests conducted by NASA (Ref 55) and given in Figures 3.12 and 3.13 are also given in Table 5.12 for comparison.

The measured friction values for ice in Canada are higher than values measured by ground vehicles in the NASA tests. The runway condition reports indicate that ice is treated with sand or urea to improve the friction when runway conditions are icy and this accounts, in part, for the difference in μ. Allowance was made for the treatment of ice when selecting representative values of aircraft-runway friction used in the risk model. The Canadian values of μ for loose snow covered runways is also much higher than those found by NASA. The greater depth of snow in the NASA tests, 1.5 in. compared to average of 0.6 in. with less than 0.1 in. 60% of the time, could account for the difference.

Table 5.12 Runway Friction Measured by Ground Vehicles - Mean Canadian Values and Range of Values from NASA Tests, and Estimated Aircraft-Runway Friction

Runway Condition	Ground Vehicle μ:		Aircraft-runway, μ
	Canada Mean*	NASA tests Range	Estimated #
Bare and dry	0.77	0.7 - 1.0	0.50
Bare and wet	0.67	0.4 - 0.9	0.27
Loose snow	0.41	0.05- 0.2	0.20
Slush	0.39	0.1 - 0.4	0.19
Frost	0.42		0.21
Ice patches	0.35	0.1 - 0.2	0.16

* Based on friction values when more than half runway is in the particular condition and, in calculating the mean value, it was assumed that when no friction value was given, the value corresponded to the 75% percentile of the known values.

# Aircraft-runway μ calculated from ground vehicle μ using Ref. 56 Table IV (page 34) for wet runway, equation (5) (page 15) for snow and ice-covered runway and average of aircraft μ on dry runway.

The friction between aircraft tires and the runway, as discussed in Section 3.4.2, are typically about one to two thirds of the values measured using a ground vehicle, depending on the form of contamination. The approximate aircraft-runway friction values under various typical types of runway conditions are also given in Table 5.12.

5.4.2 Summer Runway Conditions

Runway conditions in the summer months (April to October) are not recorded on a daily basis. Runway friction measurements are taken to track rubber build-up and monitor the condition of the runway when dry, but the frequency of wet or flooded runways is not recorded. Data on the number of hours when precipitation was recorded for each airport was used to estimate the runway conditions. The number of hours of precipitation was used as a proxy for the frequency of the runway being wet or water covered. When rainfall is recorded in a given hour, there will usually be some periods during the hour when rain does not fall. This is offset by the time the runway remains wet after the rainfall ceases. It was assumed that these two periods are roughly equal so that the proportion of time when the runway is wet is equal to the proportion of hours when rainfall occurred.

The frequency of precipitation at the six airports during the summer months is given in Table 5.13. During the period April to October the runways of these six airports are wet between 5% and 25% of the time, but this varies greatly from airport to airport as shown in the Table.

Table 5.13 Percentage of the Time Runways are Wet During the Summer Months at Six Airports*

Month	Toronto	Ottawa	Halifax	Calgary	Edmonton	Pr.George
April	14%	16%	25%	15%	10%	10%
May	10%	12%	19%	12%	9%	12%
June	7%	9%	15%	12%	11%	14%
July	5%	6%	13%	8%	9%	11%
Aug.	6%	7%	12%	8%	9%	12%
Sept	9%	10%	14%	11%	11%	14%
Oct.	11%	14%	16%	8%	8%	15%
Average	8.9%	10.6%	16.3%	10.6%	9.6%	12.6%

* Based on frequency of precipitation in each hour.

Standing water (depth > 3 mm or 0.1 in.) only occurs on high quality runways during periods of heavy rainfall. In zero wind and with a crossfall of 1 in 150 (low for runways), a rainfall of approximately 0.75 inches per hour will produce a water depth of nearly 5 mm (0.2 inches) at the center line of a runway 150 feet wide (Ref 12). Data on the rainfall rate over short periods, and frequency and duration of heavy rainfall is not available from Environment Canada. It was therefore assumed that, given rain fell in a given hour, the probability that it was heavy rain was 1/20 and that on average it lasts 1/10 of an hour. Thus, the probability the entire runway has standing water at any given time is estimated to be between 0.0003 and 0.0013 at the six airports in the summer period.

5.5 Methodology For Risk Analysis Model

A model was developed to estimate the accelerate-stop and take-off distances for a particular aircraft type at a particular airport under actual take-off conditions. The model predicts the margin of safety available on take-off, the effects of reverse thrust and variable pilot response time to abort, and the probability of a take-off accident/incident under current regulations. The model can be used to calculate the current level of risk on take-off and, in Phase II of the project, to determine the effect of contaminated runway counter measures on accident risk.

5.5.1 Probabilistic Approach

The risk analysis uses a probabilistic approach to determine the risk of an overshoot accident/incident or failure of the aircraft to clear a 35 foot screen height at the end of the runway.

For a particular aircraft, at a particular airport, the distance required to accelerate and stop the aircraft, or clear the screen height, is calculated for particular weather conditions, on a particular runway with particular runway conditions, for a particular take-off weight and a particular type of critical event at a particular speed. The margin of safety for a critical event occurring at V_1 speed and the required accelerate-stop and continued take-off distance for a critical event at any speed are calculated. The additional runway required to prevent an accident/incident in an aborted and continued take-off is calculated by subtracting the distance available for the particular runway from the required accelerate-stop or take-off distance.

By entering the conditional probabilities of these various events, and summing over all combinations of events, the probability distributions of the margin of safety and additional runway length required can be determined. The additional runway distances required are used as a measure of the severity of the accident/incident in the analyses. The expected number of accidents can be found by multiplying the accident probabilities by the number of departures.

5.5.2 Characteristics Affecting Accelerate-stop and Take-off Distances

The characteristics affecting accelerate-stop and take-off distances for a particular aircraft and airport used in the risk model are given in Table 5.14. The relationships used in the model between the characteristics and time of day and year, and other characteristics are also given. Where the characteristics are related to other variables not considered in the model, the characteristics are assumed to have a random element and a probability distribution for that characteristic is used in the risk analysis.

Variations in characteristics by time of year are modelled by using conditional probability distributions of the characteristics for each month of the year. An assumption is made that, for a given month, the wind, temperature, runway condition and weight demand for departure are all independent. This assumption is not strictly correct, but should have little affect on the results.

Variation in air density is assumed to be determined completely by pressure-altitude and temperature and, although air pressure at a given altitude is variable, it was not considered necessary to include a random element for air pressure in the model.

The departure frequency varies by month and time of day. As ambient temperature and weight demand at take-off also vary by month and time of day, this variation in the number of departures must be taken into account. This was done by including the probability of a departure for a given time and month which was estimated from Statistics Canada departure data. The effect of variation in wind speed and direction by time of day was not included in the model.

The assumption is made that environmental and runway conditions affect the accelerate-stop and take-off distances, but that they do not affect the decision on when a flight will depart. The runway condition reports for Ottawa (also used for Toronto) include when the runway is closed and runway conditions at these times were not used in determining the distribution of runway conditions on take-off.

Table 5.14 Characteristics Affecting Accelerate-stop and Take -off Distances for a Particular Aircraft and Airport

Characteristic	Symbol*	Characterizes:	Depends on:
Wind Direction	WD	Wind direction relative to runway	Time of year & random element
Wind Speed	WS	Wind speed (head and cross wind components)	Time of year & random element
Runway Number	RN	Runway used for take-off	Wind speed & dir., weight demand and random element
Air Density		Density of air	Pressure-altitude and temperature
Temperature	T	Temperature at time of take-off	Time of day & year and random element
Runway Condition	RC	Type of contamination on runway	Time of year and random element
Allowed take-off Weight	ATOW	Maximum allowed take-off weight given runway and environmental conditions	Aircraft type, wind, air density & runway
Weight Demand at Take-off	DW	Take-off weight demand, including fuel, cargo & passengers	Aircraft type, time of day & year and random element
Actual Take-off Weight	TOW	Actual dispatch take-off weight on departure	Minimum of ATOW and DW
Critical Event	CE	Type of critical event (engine failure or	Number of engines and random element other event)
Time of Critical Event	TE	Time of critical event on take-off run	Type of critical event & random element
Pilot Response Time	t_r	Time between critical event and application of braking devices	Fixed to 2 seconds or dependent on random element
Reverse Thrust	REV	Reverse thrust used in aborted take-off	Wind, type of critical event and random element

* Symbol used in equations in Appendix E

Details on the risk model and computer program, including equations for estimating accelerate-stop and take-off distances under various conditions, data sources, calibration of the model and outputs are given in Appendix E. The results of the analysis are discussed in the next two sections.

5.5.3 Take-off Weight Data Used in Risk Model

The data used to estimate the distribution of take-off weights for types of aircraft at the six airports, discussed in Section 5.3, covered a 12 month period during 1988-1989. At that time there were no departures of the A320 or BA146 aircraft in Canada and there were few (less than 10) departures of the B747 from Ottawa or Halifax. Therefore, the weight distributions could not be estimated directly from load data for those aircraft and airports. As take-off weight is an essential component of the risk model, it was necessary to estimate reasonable values for the distribution if the margin of safety and accident/incident probabilities were to be found.

In Section 5.3, the weights are presented in the form of percentage under allowable take-off weights (%UATOW) which allows easy comparison of the take-off weights between aircraft types. For the one aircraft type, there is little variation in %UATOW between airports, even the smaller airports where the ATOW may be less than the MTOW for some types of aircraft. The variation in %UATOW between aircraft types is, however, considerable. Therefore, the criteria used to select the distribution was that it should be:

- the distribution for the same (where possible) or similar type of aircraft;
- the distribution, given the most appropriate type of aircraft, from the same airport where possible; and
- reasonably typical of the distributions, either for that aircraft at other airports, or aircraft in general.

The take-off weight distributions used in the analyses are given in Table 5.15. Data for the A310 were used for the A320 and data for the B737 were used for the A146. No data was available for the A310 from Halifax so the data from Ottawa

Table 5.15 Distribution of the Percentage Under Allowed Take-off Weight and Source of Data Used in Risk Model

Aircraft	Airport	% Under ATOW #		
		Mean (SD)	Data from	
B747	Toronto	17.7 (5.9)	Toronto	B747
	Calgary	19.8 (6.6)	Calgary	B747
	Ottawa	17.7 (5.9)	Toronto	B747
	Halifax	17.7 (5.9)	Toronto	B747
A320	Toronto	10.7 (3.4)	Toronto	A310
	Calgary	11.6 (3.1)	Calgary	A310
	Ottawa	14.1 (2.2)	Ottawa	A310
	Halifax	14.1 (2.2)	Ottawa	A310
BA146	Calgary	12.9 (5.5)	Calgary	B737
	Ottawa	14.7 (5.2)	Ottawa	B737
	Halifax	13.3 (5.6)	Halifax	B737
	Prince George	15.3 (5.0)	Pr.George	B737
	Edmonton Mun.	14.7 (4.7)	Edm. Mun.	B737

was used instead. These distributions were well within the range of distributions and close to the median for the aircraft and airports given in Table 5.8. The B737 is a significantly bigger aircraft than the BA146, but their take-off performance, as measured by the ratio of the MTOW to required runway length, are quite similar; 22 lbs/ft for the BA146 and between 15 and 21 lbs/ft for the B737, depending on the model number.

The distribution of %UATOW for the B747 from Ottawa and Halifax are based on data for the B747 from Toronto as the number of departures from Toronto are greater than for Calgary and the distribution is more stable.

The actual distributions of the take-off weights will likely differ from those used in the risk analysis, but, based on the values given in Table 5.8, the mean difference is unlikely to be greater than 5%. The affect of this order of error in the weight distributions on the estimated take-off distances and the margins of safety and accident risk can determined. If the mean value of the %UATOW is 10% rather than 15%, the required take-off distances will be underestimated by about

1,100 ft for a B747, 800 ft for an A320 and 300 ft for a BA146 on a dry runway. On the other hand, if the mean value of the %UATOW is 15% rather than 10%, the required take-off distances will be overestimated by about those distances on a dry runway. On wet and contaminated runways these errors in the distance will increase, but the error as a percentage of the required distance will remain roughly constant.

Thus, when interpreting the results given in the following sections, the effect on the margins of safety and additional runway required of the substitution of load data for the A320 and BA146, and for the B747 at Ottawa and Halifax should be kept in mind.

5.6 Safety Margins For Take-offs On Dry Runways

The margin of safety on take-off is defined in Section 5.1.1. The current regulations restrict the take-off weight so that the aircraft can take-off on a dry runway if an engine failure occurs after V_1, or can take-off with 15% of the runway to spare if no engine failure occurs, or can accelerate and stop the aircraft on the runway if a critical event occurs at V_1. The full margin of safety provided by the regulations is only available on dry runways as the effects of wet and contaminated runways are not included in the calculation of maximum take-off weight under current regulations.

The risk model was used to estimate the frequency with which the allowed takeoff weight is runway restricted, i.e., ATOW is less than MTOW, and the distribution of the margin of safety for the B747, A320 and BA146 at the six airports. The full set of results from the risk analysis program are given in Appendix E.

When the allowed take-off weight is restricted by the runway length available (ATOW < MTOW), there is no safety margin on dry runways when the aircraft is at that allowed take-off weight. Table 5.16 gives the percentage of departures where the allowed take-off weight was runway restricted for the B747 and A320 determined from the risk model. Large aircraft such as the B747 have the allowed take-off weight runway restricted at all but the longest runways. For smaller aircraft the frequency with which this occurs is very dependent on the aircraft type and airport, as shown in the table. The BA146 ATOW was not runway restricted at any of the 6 airports considered.

When the actual take-off weight, TOW, must be reduced to the maximum allowed, ATOW, there is zero margin of safety on dry runways. The frequency with which this occurs was estimated using the risk model and is given in Table 5.16. Also given is the percentage of departures where the margin of safety on dry runways is less than 1000 feet. Most departures have some margin of safety on dry runways, but roughly 10 to 20% of departures of the B747 and A320 from Calgary, Ottawa and Halifax have a safety margin of less than 1000 feet. The actual take-off weight of the BA146 was not restricted to the MTOW at any of the six airports considered and the safety margin on dry runways was greater than 1000 feet in all cases.

Table 5.16 Estimated Distribution of Margin of Safety on Dry Runway and Percentage of Take-offs Where Allowed Take-off Weight is Runway Restricted[a]

Aircraft	Airport	% of Take-offs on Dry Runway where:		
		ATOW less less than MTOW	Safety Margin Zero	<1000 ft [illegible]
B747	Toronto	80%	0%	1%
	Calgary	94%	15%	16%
	Ottawa	99%	3%	6%
	Halifax	100%	1%	5%
A320	Toronto	5%	0%	0%
	Calgary	27%	20%	33%
	Ottawa	70%	1%	17%
	Halifax	66%	0%	13%
BA146	Ottawa	0%	0%	0%
	Halifax	0%	0%	0%
	Prince George	0%	0%	0%
	Edmonton Mun.	0%	0%	0%

[a] Safety margin defined in Section 5.1.1 for aborted take-offs at V_1; except for B747 from Toronto and Calgary, % based on weight distribution for another aircraft as given in Table 5.15.

Table 5.16 also gives the percentage of take-offs where the margin of safety for an aborted take-off at V_1 on a dry runway is less than 1000 feet. The percentages vary considerably with aircraft type and airport with almost all departures from Toronto having a margin of safety of greater than 1000 feet, but only 81% of A320 departures from Ottawa and 84% of B747 departures from Calgary have that safety margin.

The distribution of the margin of safety on a dry runway is given in Figure 5.6 for B747 departures from Toronto airport and Figure 5.7 for the BA146 from Edmonton Municipal airport. The distributions are given both for when the aircraft is at ATOW and when at its actual take-off weight are given. Clearly for the B747 at Toronto there is little margin of safety at ATOW, but at actual take-off weights most departures have significant runway to spare in dry conditions. Similarly, the BA146 departures from Edmonton Municipal airport have a fairly large safety margin on a dry runway, but unlike the B747, much of it is available even when the aircraft is at ATOW.

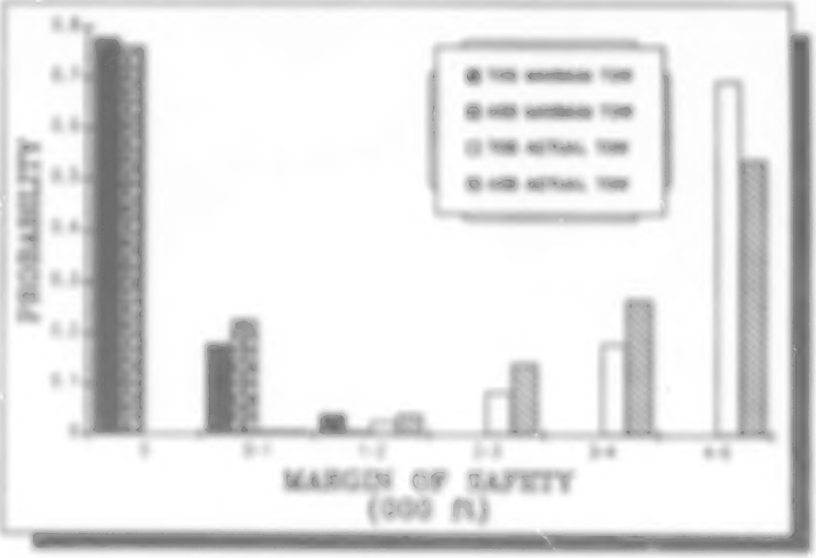


Figure 5.6 Distribution of the Margin of Safety on Take-off from Dry Runways for the B747 at Allowed and Actual Take-off Weight for Departures from Toronto

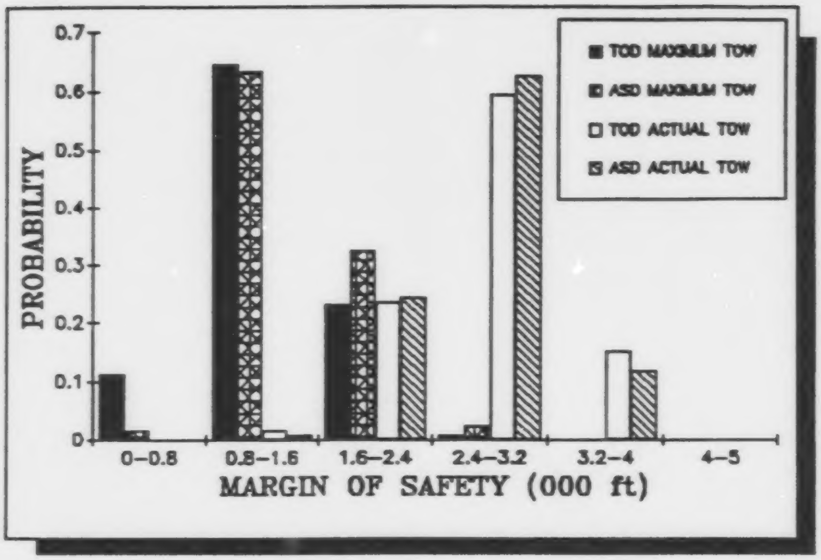


Figure 5.7 Distribution of the Margin of Safety on Take-off from Dry Runways for the BA146 at Allowed and Actual* Take-off Weight for Departures from Edmonton Municipal Airport

* "Actual" based on distribution of %UATOW for B737

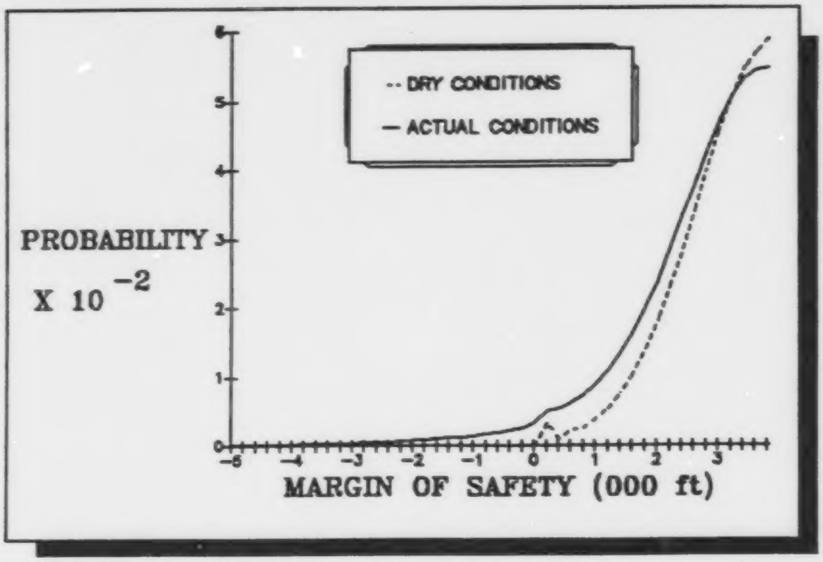
5.7 Take-off Accident Risk Under Actual Runway Conditions

As discussed in Section 5.4, runway conditions significantly alter the accelerate-stop and take-off distances. The margin of safety provided by current regulations are applicable only in dry conditions and do not truly reflect the safety of the take-off under actual runway conditions. The risk model was used to estimate the effect on the actual margin of safety of allowing for runway conditions. Initially, results are given assuming that reverse thrust is not used in aborted take-offs and that the pilot reaction/decision time is the 2 second standard time allowed in the regulations. The effects of reverse thrust and variable reaction time are then considered. The results from the risk analysis program are given in Appendix E.

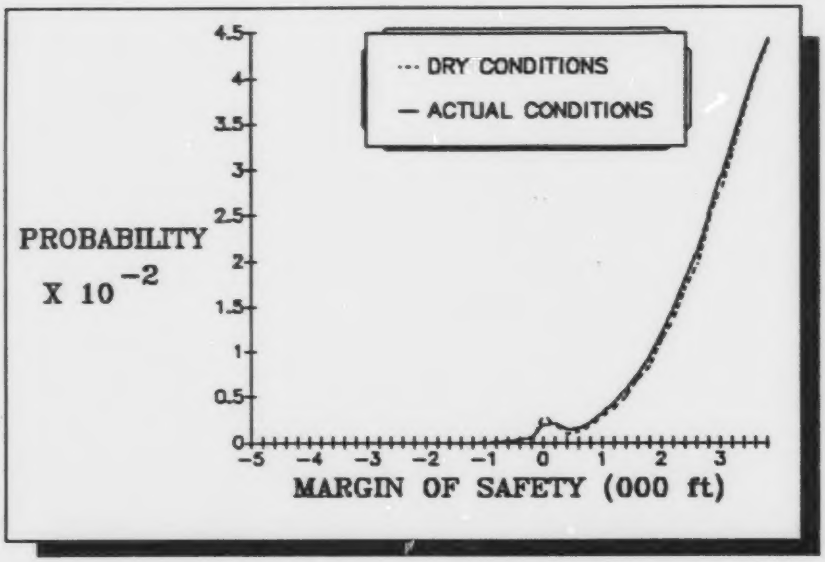
The distributions of the margins of safety under dry and actual conditions are given in Figure 5.8 for the B747 at Toronto and in Figure 5.9 for the A320 from Halifax. In the comparison, the same take-off weights under dry and actual conditions are used and, as specified in the current regulations, the TOW's are less than the ATOW calculated for dry conditions. The margin of safety is significantly reduced when the effect of runway contamination is included. Under dry conditions there is always additional runway available, but under actual runway conditions the safety margin falls to below zero. Thus, if a critical event occurred at V_1, 2.2% of aborted take-offs (with reverse thrust not used) for the B747 from Toronto, would overrun the runway and 0.1% of continued take-offs would fail to clear a 35 ft obstacle at the end of the runway. Similarly, 28% of aborted take-offs (with reverse thrust not used) for the A320 from Halifax would overrun the runway, but all continued take-offs would clear a 35 ft screen height.

The probabilities given in Figures 5.7 and 5.8 relate to the risk of an accident/incident when a critical event occurs at the decision speed, V_1. The risk of any departure resulting in a take-off accident/incident is much less as the probability of a critical event occurring near V_1 is very small; of the order of 10^{-5} to 10^{-6} (see Section 5.2). An accident/incident is possible without the occurrence of an engine failure on a contaminated runway if the contaminant increases the all engine take-off distance by more than 15% of the take-off distance on a dry runway and the take-off weight is restricted for an all engine take-off. This occurs, for example, for the A320 on a runway covered completely with more than 1/2 inch of slush or one inch of snow (see Figure 4.25), or for the BA146 with more than 1/3 inch of water or slush (see Figure 4.33). However, as these types of conditions occur very infrequently (see Section 5.4) and the runway would often be closed under these conditions, the risk of an accident/incident not preceded by a critical event was not considered in the risk model.

Comparisons of the risk of an accident/incident at times of different runway conditions shows the penalty, in terms of safety, of ignoring runway conditions in the calculation of take-off performance and TOW. Figure 5.10 gives the risk of an overrun accident/incident for the B747 from Toronto airport during January for the three cases when the runway is 100% ice patches, loose snow covered (20 mm) or bare and wet. The corresponding accident/incident probability on a dry runway is zero. On a wet runway the risk is still very low, 10^{-7}, but on snow covered runways this increases to less than 10^{-6}, and on an ice covered runway the chances of a very serious accident (overrun of more than 4000 ft) is 2×10^{-6}. The risk on a runway with 8 mm of slush is very similar to that on 20 mm of snow given in Figure 5.10. Note that these risks are for aborted take-offs where reverse thrust is not used.

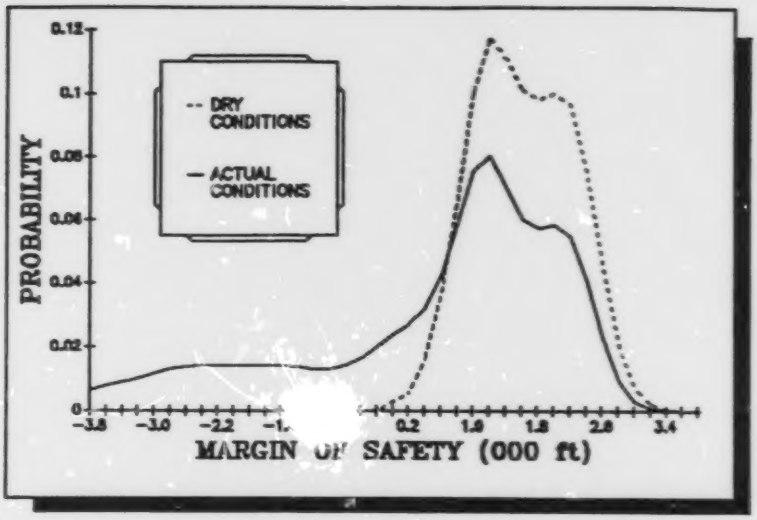


(a) Aborted Take-offs

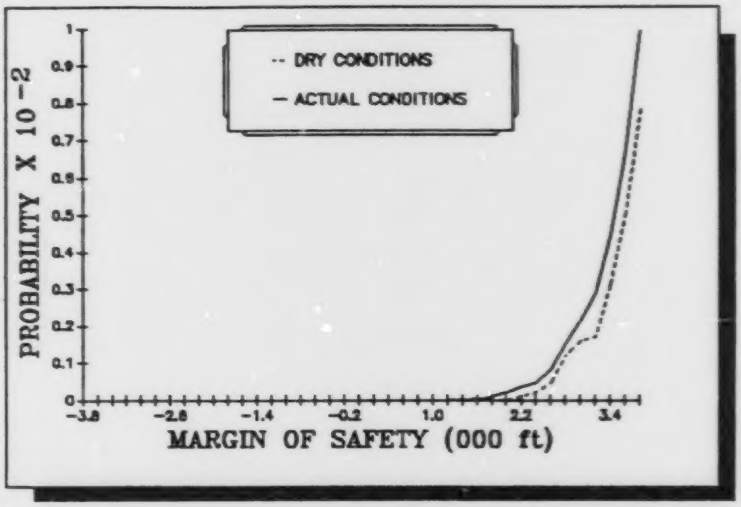


(b) Continued Take-offs

Figure 5.8 Distribution of the Margin of Safety Under Dry and Actual Runway Conditions Given Critical Event at V1 for the B747 from Toronto



(a) Aborted Take-offs



(a) Continued Take-offs

Figure 5.9 Distribution of the Margin of Safety Under Dry and Actual* Runway Conditions Given Critical Event at V1 for the A320 from Halifax

* "Actual" based on percentage under allowed take-off weight for A310 aircraft from Ottawa

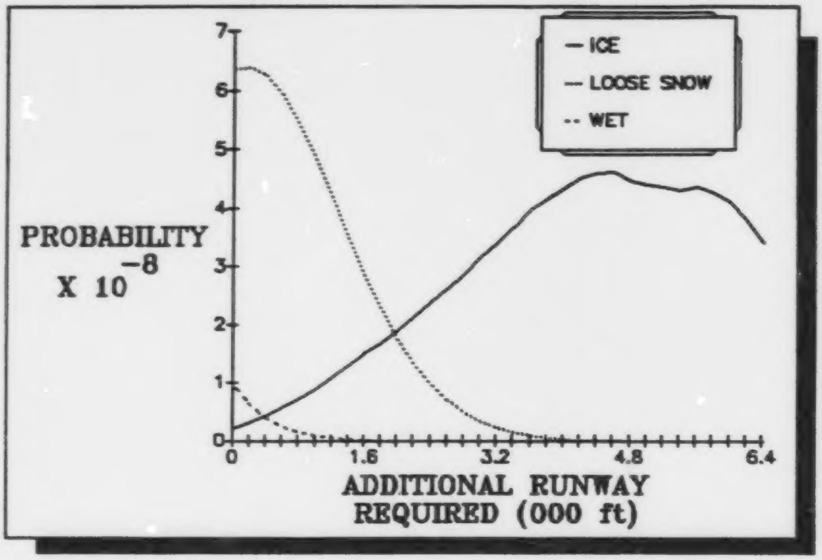
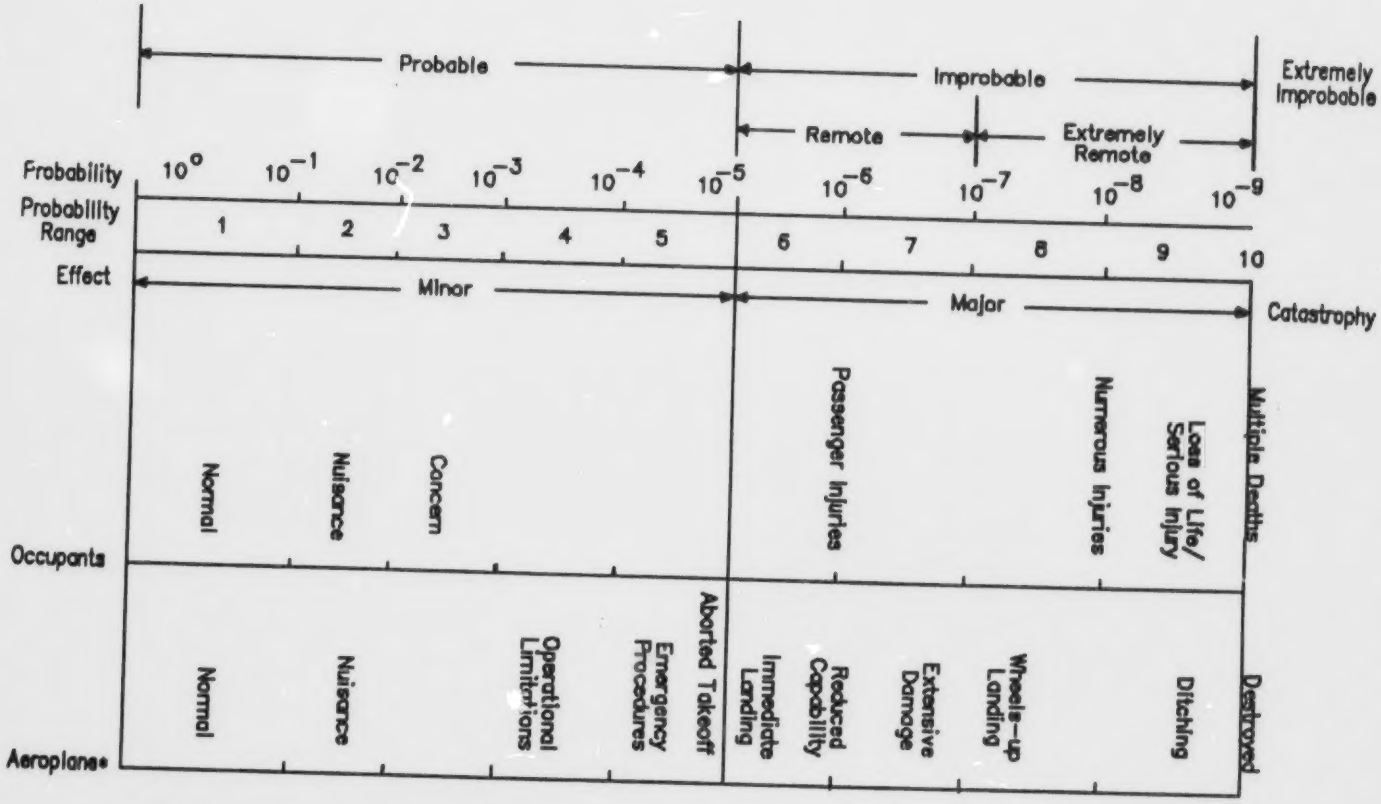


Figure 5.10 Risk of an Overrun Accident/Incident for a B747-100 from Toronto in January Given Ice, Loose Snow and Wet Runway Conditions*

* Risk equals zero on dry runway; reverse thrust not used.

These accident/incident risks can be compared with accepted severity of aircraft accidents and incidents and the probability of their occurrence. The British Civil Airworthiness Authority produced a chart showing this relationship which is given in Figure 5.11. Clearly, the risks of serious take-off accidents on snow and ice covered runways are far greater than other less serious accidents and incidents shown in the chart.

The accident/incident risk and the distribution of the additional runway required over all months of the year and all runway conditions is given in Table 5.17 for the aircraft and airports considered in the analysis. Again, if runway conditions were always bare and dry, as assumed by the current regulations, the risks would be zero. The distribution of risk for B747 departures from Toronto are shown in Figure 5.12. The risks, as expected, vary greatly with aircraft type and airport and range from 1.5 x 10^{-6} to less than 10^{-9}. The high frequency of poor runway conditions at Halifax airport combined with the short runway length for large jet aircraft


Probable
Improbable
Extremely Improbable
Remote
Extremely Remote
Probability
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
Probability Range
1
2
3
4
5
6
7
8
9
10
Effect
Minor
Major
Catastrophy
Occupants
Normal
Nuisance
Concern
Passenger Injuries
Numerous Injuries
Loss of Life/ Serious Injury
Multiple Deaths
Aeroplane*
Normal
Nuisance
Operational Limitations
Emergency Procedures
Aborted Takeoff
Immediate Landing
Reduced Capability
Extensive Damage
Wheels-up Landing
Ditching
Destroyed

*The positions of some of the items on this scale will vary for different aeroplane designs

Figure 5.11 Relationship Between Probability and Severity of Effects

Source: British Civil Airworthiness Requirements, Paper No. 670, 3rd Sept. 1976.

Table 5.17 Accident/Incident Risk and Probability Distribution of Additional Runway Required*

Aircraft	Probability x 10^{-6} of Additional Distance Required (ft)						
/Airport	0 - 2000		2000 - 4000		> 4000		Accident/ Incident
	ASD	TOD	ASD	TOD	ASD	TOD	
B747							
Toronto	.066	.027	.018	.000	.003	.003	.115
Calgary	.080	.176	.006	.000	.001	.000	.263
Ottawa	.132	.062	.028	.000	.004	.000	.225
Halifax	.296	.034	.052	.000	.004	.000	.387
A320							
Toronto	.163	.007	.050	.002	.007	.001	.229
Calgary	.119	.003	.024	.001	.004	.000	.150
Ottawa	.361	.000	.103	.000	.013	.000	.476
Halifax	1.11	.000	.356	.000	.038	.000	1.500
BA146							
Toronto	.000	.000	.000	.000	.000	.000	.000
Calgary	.000	.000	.000	.000	.000	.000	.000
Ottawa	.000	.000	.000	.000	.000	.000	.000
Halifax	.000	.000	.000	.000	.000	.000	.000
Pr.George	.008	.013	.000	.000	.000	.000	.021
Edm.Mun.	.039	.004	.001	.000	.000	.000	.044

* Risk of less than 10^{-9} given as .000; based on TOW data given in Table 5.15.

result in a relatively high risk for take-offs from Halifax. The accident risk of the small BA146 aircraft is low, even at Edmonton Municipal airport which has a runway length of 5868 ft at an elevation of 2200 ft (which is roughly equivalent to a 5070 ft runway at sea level). At the larger airports the risk of any form of take-off accident/incident is less than 10^{-9} for the BA146.

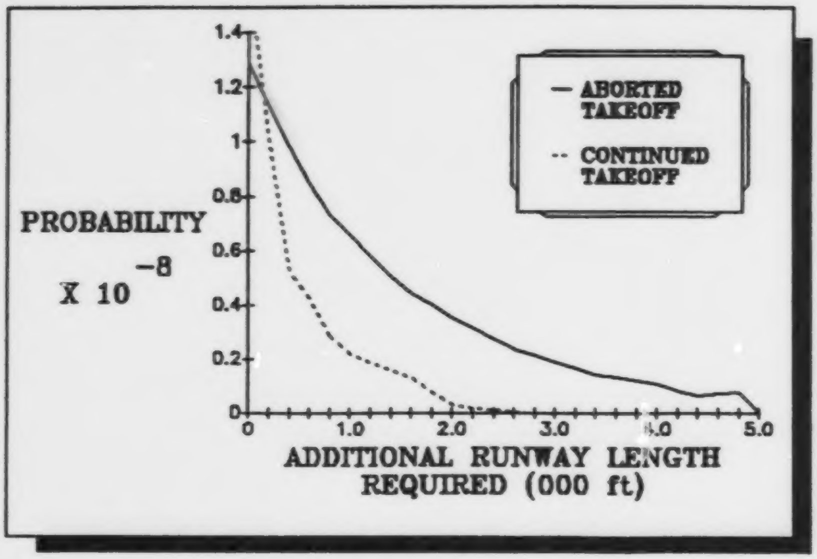


Figure 5.12 Risk of a Take-off Accident/Incident for B747 at Toronto

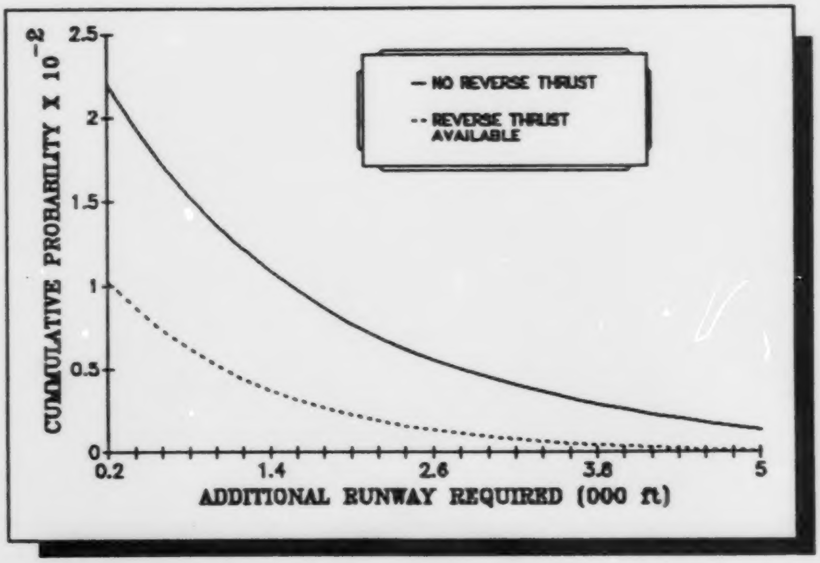


Figure 5.13 Effect of Reverse Thrust on the Risk of an Overrun Accident/Incident for a B747 from Toronto When Critical event Occurs at V1

Effect of Reverse Thrust

Currently credit for reverse thrust has not been included in the calculation of the ASD and maximum take-off weight for aircraft in the U.S. and for only the BAC111 in Canada as the aircraft manufactures have not elected to demonstrate the aircraft meets the requirements of FAR 25.109. However, reverse thrust is often used in aborted take-offs and can be especially effective when wheel braking is poor due to low friction. Use of reverse thrust can reduce the pilot's ability to control the aircraft during the deceleration, especially if a wing engine has failed and use of reverse thrust in the other wing engine(s) compounds the effect of a cross wind. As discussed in Appendix E-8, reverse thrust is therefore assumed to **not** be used in these situations in the risk model.

In estimating the accelerate-stop distance, credit for reverse thrust is given only for those engines which have not failed at a level of approximately 60% of maximum reverse thrust and it is assumed to be the last braking device applied.

The effect of reverse thrust on the risk of an overrun accident/incident for aborted take-offs from the V_1 speed is given in Figure 5.13 for the B747 from Toronto. The figure shows that use of reverse thrust reduces the risk for the more serious overruns (more than 4000 ft) by about 90% and reduces the risk of any overrun accident/incident by almost a half. More generally, use of reverse thrust was found to reduce the risk of serious overruns by a third and of any overrun by 25%.

Variable Pilot Response Time

The regulations include in the calculation of ASD a two second period between the time V_1 speed is reached and the time when braking is commenced. This period is included to allow time for the pilot to identify a critical event, decide whether to abort the take-off and actually commence braking. The decision and reaction time in practice varies depending on the pilot and the circumstances, and long delays in deciding to abort the take-off are frequently given as a factor in overrun accidents (see Section 2.2.5).

The risk model analysis was run using a variable response time to determine if this had a significant effect on the accident risk, especially under actual runway conditions. The distribution of the response time, given in Appendix E-7, has a mean value of 1.91 seconds, but allows response times of over 5 seconds with a probability of 0.0007. The distribution is only approximate, but gives a good indication of the effect on the accelerate-stop distance of allowing the response time to be variable.

Use of a variable response time had effect little on the overall probability of an overrun accident/incident, but increased the probability of the worst types of accidents (i.e., those with the greatest additional runway distance required).

5.8 Risk Analysis Findings

5.8.1 Frequency of Critical Conditions

1. There are almost half a million jet aircraft departures in Canada each year; engine failures occur once every 76,000 departures and some other type of critical event (which would lead to an aborted take-off if it occurs before V_1 speed) occurs once every 40,000 departures.

2. Aircraft rarely take-off at the allowed maximum take-off weight and typically have take-off weights between 5% and 20% less than the allowed take-off weight, ATOW. This amount under ATOW translates into a safety margin on take-off of 10% to 35% of the required take-off distance for the aircraft.

5.8.2 Runway Conditions

1. Runways in Canada during the coldest 5 months are wet or contaminated, on average, about a third of the time, but this can vary from 10-65% of the time depending on the airport and month. During December to February the runways are snow covered 10-30% of the time, ice covered 2-20% of the time, slush covered 2-3% of the time, and frost covered 1-3% of the time

2. During the periods when runways are contaminated, typical depths of runway contaminants in Canada are 0.6 in. of loose snow, 1.5 in. of drifting snow and 0.3 in. of slush.

3. The runway friction measured using a ground vehicle varies significantly for the same type of contaminant, but average values are 0.8 for bare and dry, 0.7 for bare and wet, 0.4 for snow, slush or frost and 0.35 for ice patches.

4. During the warmer months runways are wet between 5 and 15% of the time at most airports, but this varies greatly with month and airport.

5.8.3 Accident/Incident Risk

1. For the B747, A320 and BA146 most departures (more than 80%) have a required runway length, based on calculations for a dry runway, at least 1,000 feet less than the available runway length.

2. The current regulations were designed so that if a critical event occurs at the V_1 speed, the aircraft could abort take-off and stop on the runway. However, in Canada there is a probability that roughly 1 in every 1000 aircraft aborting take-off at V_1 speed would not be able to stop due to the performance calculations not including actual runways conditions, and the chance of a serious accident is roughly 1 in 10,000.

3. At Toronto airport when a B747 aircraft lines up for take-off on a snow covered runway the probability of an overshoot accident is 1×10^{-6} and on a 100% ice covered runway the probability of a serious accident (overrun by 4,000 ft) is one in 500,000; much greater than acceptable risks due to other types of aviation accidents.

4. The take-off accident risks for B747 and A320 departures vary from about 0.1×10^{-6} for departures from Toronto to 1.5×10^{-6} for departures from Halifax. Accident risks for the BA146 are less than 10^{-9} at Toronto, Calgary, Ottawa and Halifax and are between 10^{-8} and 10^{-7} for Prince George and Edmonton municipal airports.

5. Use of reverse thrust reduces the take-off accident risk by 25% and reduces the risk of a serious accident by about a third.

6. CLASSIFICATION SYSTEM FOR RUNWAY CONDITIONS

6.1 General

Currently, national systems used to describe or report runway condition/friction during contaminated conditions, differ sufficiently to lack credibility with the pilot community. Even terminology which describes braking effectiveness such as excellent, good, marginal and poor are inconclusive or inconsistent.

The subject was discussed by international attendees at the NASA/FAA Runway Friction Workshop held at the NASA Langley Research Center on October 26 & 27, 1988. Several attendees indicated interest and motivation to develop universality in runway friction accountability.

Many airline pilots and airport operators stated that they would like to see a standardized approach rather than have either an individual country or airport approach, and the general opinion was to use the ICAO terminology and definitions of Annexes 14 and 15.

Two exceptions to the possible universality of the ICAO approach have been identified during this study, namely one by Airbus Industrie and the other by the Aircraft Operations Group of the Cranfield Institute of Technology. Other sources were identified where there was no direct disagreement with the ICAO SARPS but there was dissatisfaction with the fact that runway friction measurement devices fail to reliably predict aeroplane braking action on contaminated runways in "day to day" operations.

6.1.1 Airbus Industrie Position

The Airbus Industrie Engineering Directorate, Flight Division Report (Ref. No. 33) to the 5th Performance and Operations Conference May 1988, expressed concern about the correlation between the test results of the DBV and SFT friction test devices and the A310. It stated "Airbus Industrie does not intend (for the time being) to establish a correspondence between the published performance and an "Estimated Braking Action Scale". It is therefore recommended to obtain from Airport Authorities a report on actual state of the runway in terms of kind of contamination and measured depth."

6.1.2 Cranfield Institute of Technology

The Aircraft Ground Operations Group of the Cranfield Institute of Technology reported in 1988 on its attempts to duplicate the ICAO data, specifically Figure 5.1 in Part 2 of the Airport Services Manual (Doc 9137-AN898). In Ref. 57 Report CAA/TN-88-135, the first conclusion states "The results of the U.S.A. and ICAO compacted snow and ice trials do not agree even though they were both conducted by experts. This should be investigated before any relationship is agreed."

However, TN-88-135 is erroneous in its reporting of the U.S.A. data and incorrectly attributes it to Figure 5.1 of Doc 9137-AN898 when in fact there is strong evidence that the U.S.A. data is from NASA-TM100506 March 1988. Also the ICAO trials referred to in TN-88-135 are not the data in Figure 5.1 of Doc 9137-AN898, but rather special set of trials conducted on behalf of ICAO by the Swedish National Research Institute and the Cranfield Institute of Technology.

Thus the Cranfield conclusions are really for a comparison of the NASA-TM 100506 and CAA/TN-88-135, and do not include the ICAO Figure 5.1 Doc 9137-AN898.

Figure 6.1 illustrates the foregoing discussion and superimposes the Figure 5.1 data on Figure 3 from TN-88-135. The Figure 5.1 points fall almost precisely on curve "E" which the author states is a suggested compromise of the U.S. (curve B) and Average of European Trials (Curve D).

The importance of this observation is that the conclusion from CAA/TN-88-135 quoted above does not really find conflict with ICAO Figure 5.1 Doc 9137-AN898, in fact it could have stated U.S. and European trials differ but that their average values are almost identical to the ICAO Figure 6.2 data.

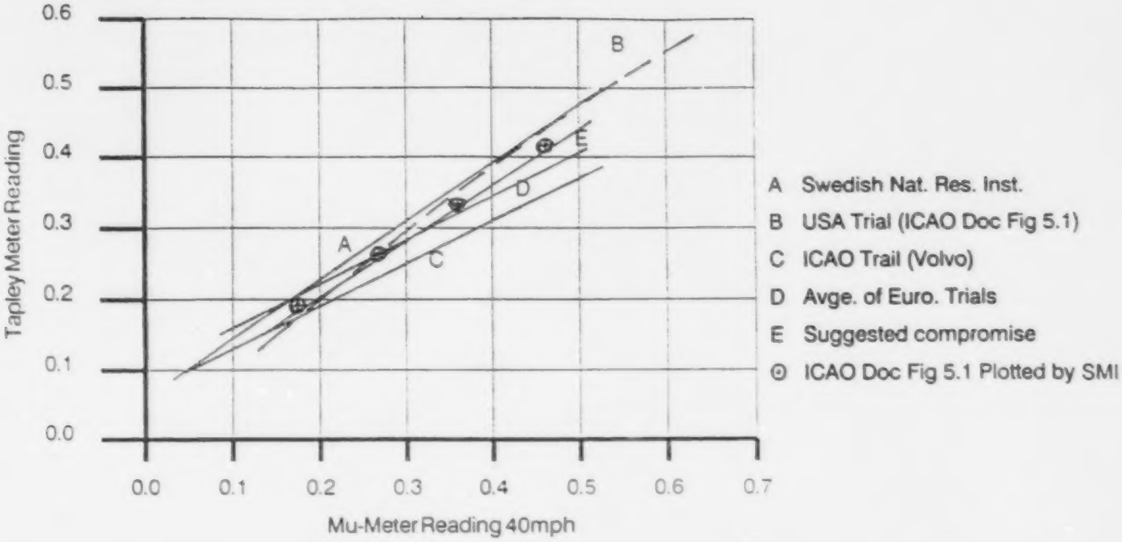


Figure 6.1 Tapley Meter v Mu-Meter Correlation in Compacted Snow and Ice Conditions

Source: Ref. 57, Fig. 3

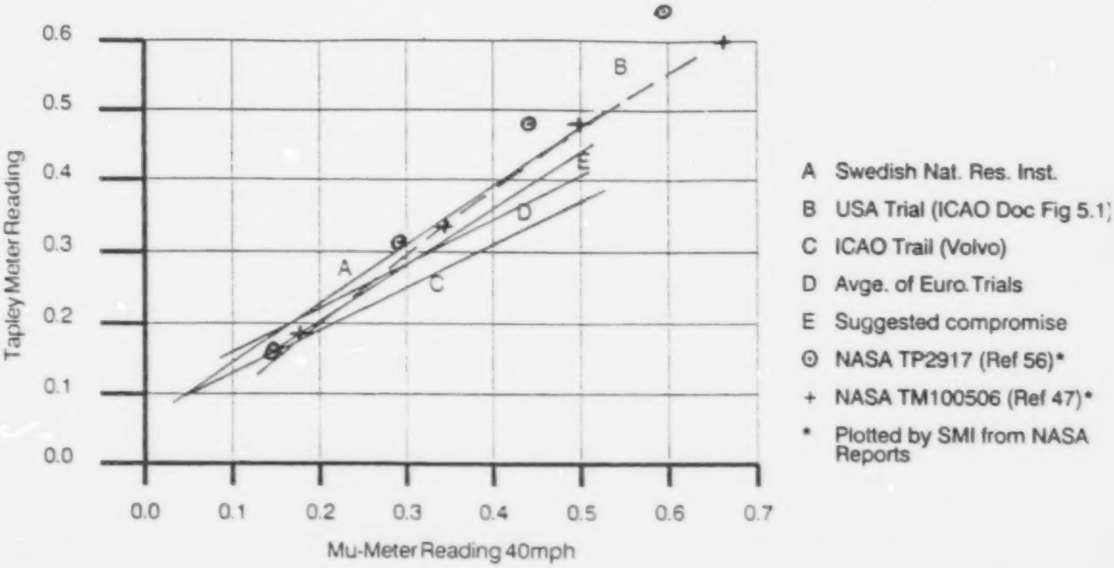


Figure 6.2 Tapley Meter v Mu-Meter Correlation in Compacted Snow and Ice Conditions

Source: Ref. 57, Fig. 3

If this is an accurate assessment of the CAA/TN-88-135 data then the literature could appear to report only one exception to the ICAO "Figure 5.1" data, namely the Airbus Industrie comments quoted in section 6.1.1.

The U.S.A. data in NASA TM-100506 has been amended by NASA TP2917 February 1990. The two sets of NASA data are illustrated in Figure 6.2 but when the new data is averaged with the European data of TN-88-135 the effect upon the curve E is not significant enough to alter the correlation of the average or compromise of U.S.A. and European data. Thus the Airbus Industrie remains the only exception found in the literature to ICAO Figure 5.1 Doc 9137-AN898 universality of the comparison of the friction index of the ground vehicle testing machines on compacted snow and ice-covered runway surfaces.

However, the Airbus Industrie position is supported by the Airworthiness Authorities of France and the UK and presumably by other of JAA member states, so there is an appearance of lack of support for Figure 5.1 Doc 9137. It will be shown in 6.2 ICAO Standards and Recommended Practices (SARPS) that none of the JAA member states has filed a difference with the Annexes 14 and 15 standards which means the SNOWTAM Format is supported and with it the data upon which it is based namely Figure 5.1 Doc. 9137. Therefore it must be concluded that support for Airbus Industrie relates solely to the values of runway friction used for calculating take-off performance on contaminated runways as per the option in the JAR 1591 Acceptable Means of Compliance, and thus does not preclude the JAA Airworthiness Authorities from not holding a difference with Annex 15.

6.2 ICAO Standards and Recommended Practices (SARPS)

Annex 15, Chapter 5 contains SARPS for Aeronautical Information Services. The standards applicable to reporting runway condition are mandatory as follows:

> "5.1.1.1q Presence or removal of significant changes in hazardous conditions due to snow, slush, ice or water on the movement area. NOTE - Notification of such conditions is to made preferably by use of the SNOWTAM format in Appendix 2 or the NOTAM Code (Doc 8400)."

> "5.5.4 Information concerning snow, ice, and standing water on aerodrome pavements shall, when reported by means of a SNOWTAM, contain the information in the order shown in the format in Appendix 2."

The SNOWTAM format and instructions of Annex 15 Appendix 2 are provided in Appendix G of this report.

Annex 15 lists the differences filed by States on each standard as follows:

5.1.1.1q	Cuba United States for taxiways and ramps. (Runways not mentioned)
5.5.4	Lesotho

Annex 14, Aerodromes SARPS, Attachment A pages 120-122, Section 6 and 7 provide guidance for measuring and expressing braking action on snow and ice covered runways and for determining the friction characteristics of wet runways. A copy is provided in Appendix H of this report.

ICAO States are not obliged to file differences with recommended practices so it is not possible to determine from the literature if the above - referenced guidance is in use by States. However, it is unlikely that States would comply with Annex 15 Standards without utilizing the Annex 14 guidelines, so it is assumed that States are generally supportive of the ICAO procedures for measuring runway friction characteristics.

Section H of the SNOWTAM format which also appears in Annex 14 Attachment A is presented for ready reference and discussion prior to reporting on the practices of States and Operators to illustrate the details of non-universality of the ICAO approach.

"SNOWTAM Section H measured/calculated or estimated braking action:

Measured or Calculated Coefficient	or	Estimated Braking Action
0.40 and up		Good
0.39 to 0.36		Medium good
0.35 to 0.30		Medium
0.29 to 0.26		Medium poor
0.25 and below		Poor
9 unreliable		Unreliable"

The text of Attachment A, 6.6 states

> "The table below with associated descriptive terms was developed from experience in compacted snow and ice with one type of decelerometer and one type of continuous measuring device at fixed speeds, and should not therefore be taken to be absolute values applicable in all conditions. If the surface is affected by snow or ice and the braking action is reported as "good", pilots should not expect to find conditions as good as on a clean dry runway (where the available friction may well be greater than needed in any case). The value "good" is a comparative value and intended to mean that aeroplane should not experience directional control or braking difficulties, especially when landing:

Measured/calculated coefficient	Estimated braking action	Code
0.40 and above	Good	5
0.39 to 0.36	Medium to good	4
0.35 to 0.30	Medium	3
0.29 to 0.26	Medium to poor	2
0.25 and below	Poor	1

The text of Attachment A, 6.8 states

> "A continuous measuring device (e.g. Skiddometer, Surface Friction Tester or Mu-meter), or a diagonal braked vehicle, can be used for measuring the friction values for compacted snow- and ice-covered runways. A decelerometer (e.g. Tapley Meter or James Brake Decelerometer) may be used on certain surface conditions, e.g., compacted snow, ice and very thin layers of dry snow. Other measuring devices can be used, provided they have been correlated with at least

> one of the types mentioned above. A decelerometer or diagonal braked vehicle should not be used in loose snow or slush, as they can give misleading friction values. Other vehicles can also give misleading friction values unless otherwise proven."

The text of Attachment A, 6.9 states

> "The Airport Services Manual, Part 2 provides guidance on the uniform use of test equipment to achieve compatible test results and other information on removal of surface contamination and improvement of braking action."

The Airport Services Manual Part 2 is provided in Appendix A.

The text of Attachment A, 7.8 states

> "The Annex recommends that States specify a friction level below which maintenance action should be taken and for reporting when runways may be slippery when wet. Experience with different measuring devices shows the following criteria in use in some States for specifying the friction characteristics of new runway surfaces and establishing maintenance levels:

Test Equipment	Design objective for new runway surface	Maintenance level	Test Water Depth (mm)	Test Speed (km/h)	
1	2	3	4	5	
Mu-meter					
method 1	0.7	0.5	1.0	65	
method 2	0.65	0.45	0.5	130	
Skiddometer and Friction Tester	0.5	0.35	1.0	130	with high pressure tire
	0.6	0.4	1.0	95	
	0.7	0.5	1.0	65	
Stradographe	0.6	0.35	1.0	65	

The values in columns (2) and (3) are averaged values representative of the runway or significant portions thereof. "

The text of Attachment A, 7.9 states

> "The measurements specified in this section may not directly correlate with aircraft performance. Research work indicates that reasonable correlation between friction measurements and the friction available for aircraft exists provided the measure values are referenced to a common base line."

Thus it is clear from the ICAO standards, recommended practices, and guidance material that measurements may not correlate with aeroplane performance, but every effort should be made to measure values on the basis of a common baseline which will enhance the correlation.

6.3 Practices of Some States

6.3.1 France

Airbus Industrie and its partners have been involved in the determination and writing of the context and requirements of JAR 25 and this regulation was used for the joint certification of the A320 by four participating airworthiness authorities. The friction coefficients utilized for A320 take-off performance are shown in Figure 6.3.

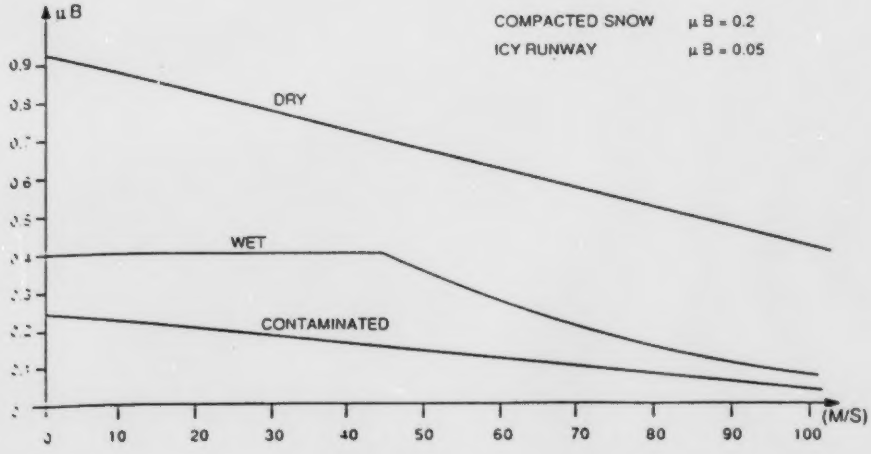


Figure 6.3 A320 Runway Friction Coefficient

Source: Ref. 33, Page5/12

- For some speed conditions μ wet is slightly less than 0.5 μ dry which is the result of experience obtained by CAA with the A310 and BAE146.
- The friction coefficient on contaminated runway is $\frac{\mu dry}{4}$
- Take-off on icy runway (μ=0.05) is not recommended.

The friction coefficients used for the A300 and A310 based on tests agreed by the CAA are shown in Figure 6.4.

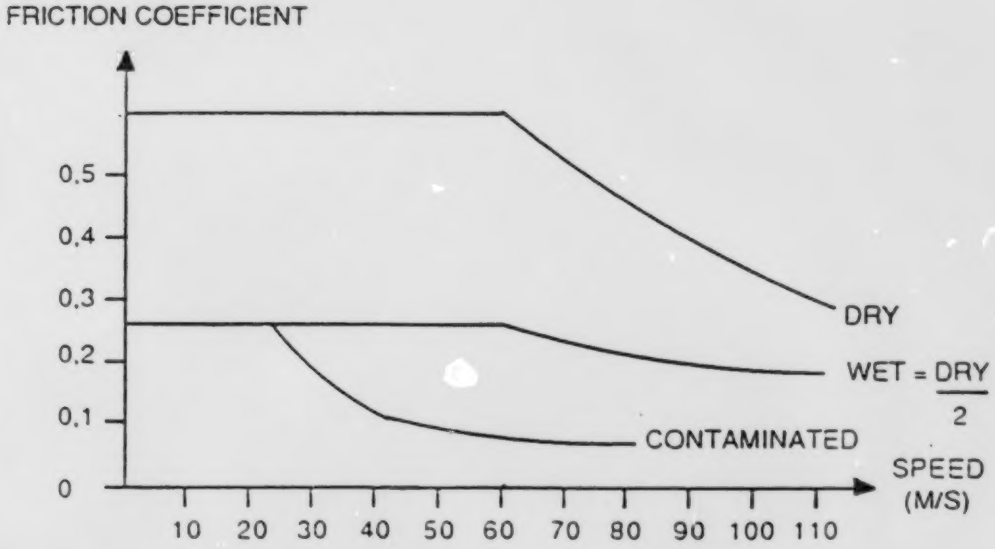


Figure 6.4 Friction Coefficient A310-A 300-600 (ICY Runway μ = 0.05)

Source: Ref. 33, Page 2/12

As was indicated in 6.1.1, Airbus Industrie does not support the use of friction values or estimates of braking action as recommended in the ICAO SARPS and prefers to have a description of the contaminant and depth.

France has not filed a difference with the ICAO SARPS, but it has approved the Airbus Industrie take-off performance for the A320. Therefore, it is reasonable to say that France supports the ICAO SARPS unless the aeroplane manufacturer establishes other conditions in the approved flight manual by test.

6.3.2 United Kingdom

The U.K has not filed a difference with the ICAO SARPS, although like France it has agreed to the Airbus Industrie take-off performance for the A320. Also, the U.K. has had a requirement for certification of take-off performance from precipitation covered runways for a number of years. Extracts from the U.K. Airworthiness Requirements are contained in Appendix A of Part III, Section 8 of the ICAO Airworthiness Technical Manual.

6.3.3 United States

The U.S.A. has not filed a difference with the ICAO SARPS for runway contamination although it has for taxiways and ramps as described in 6-2 page 6-6. Also, as indicated in 1.2.2. page 1-2, the U.S.A. does not have requirements for take-off performance accountability, but FAA AC 91-6A contains guidelines and recommendations for adjustment factors when operating from contaminated runways.

6.3.4 Sweden

Sweden has not filed a difference with ICAO SARPS for runway contamination. Each operator is required to present to the Board of Civil Operation the precautions in the form of corrections of take-off and landing distances to be applied in case of contaminants on the runway. Examples are given in 4.3 take-off performance.

6.3.5 Japan

Japan has not filed a difference with ICAO SARPS for runway contamination. All Nippon Airways and Japanese Airlines have conducted extensive tests with the B747 and Tapley and ML-MU test equipment, and developed take-off performance accountability charts.

6.3.6 Canada

Canada has not filed a difference with ICAO SARPs for runway contamination. The AIP Canada TP 2300 E contains descriptive material for the use of the James Brake Decelerometer (JBI) data by pilots. Chapter AIR 2.14 includes landing performance adjustment factors but states take-off performance data is not provided for JBI measurements pending further study of take-off performance. A table of JBI values with corresponding runway surface condition descriptions is included and provided here as Figure 6.5.

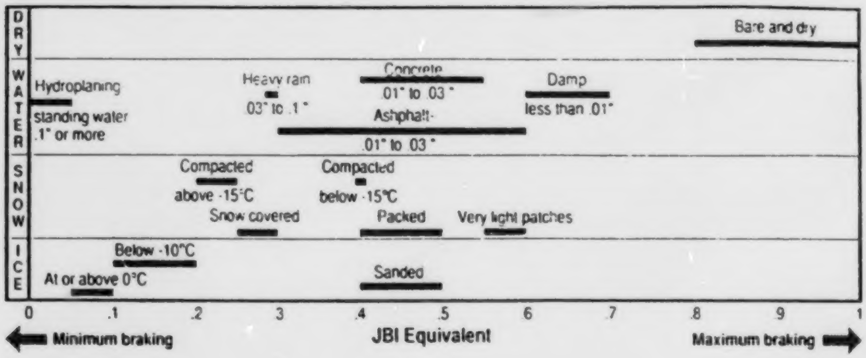


Figure 6.5 Runway Surface Condition (RSC) and JBI Equivalent

Source: A.I.P. Canada, AIR 2-23, Table D

Canada does not use the SNOWTAM format and believes that its NOTAM format is equivalent. However, in Section 5.4 Risk Analysis - Runway Conditions, and Appendix F it was stated that the frequency of occurrence of wet and contaminated runways has not been well documented and its effect on aviation safety is not clear. In part this is due to the failure to follow the ICAO SNOWTAM format, and also due to the lack of evidence of a monitoring program by either the airport or flight operations specialists of the consistency of the JBI methodology at airports both as a group and individually.

6.3.7 Military Braking Code Including NATO And Iceland Airports

Pages E14 and E15 from the VFR Supplement contain the U.S. NAVY/ARMY, U.S. AIRFORCE, NATO, CANADIAN MILITARY, AND ICELAND CODES for JBI, RCR, MU-METER measured values relevant to the code plus a plain language description of the braking action. These pages are provided in Figure 6.6. It should be noted that NATO STANAG 3634 from which the NATO data was obtained has been amended for the RCR column to read Code A, 16 and above; Code B, 14.5 to 11; and Code C, 9.5 and below.

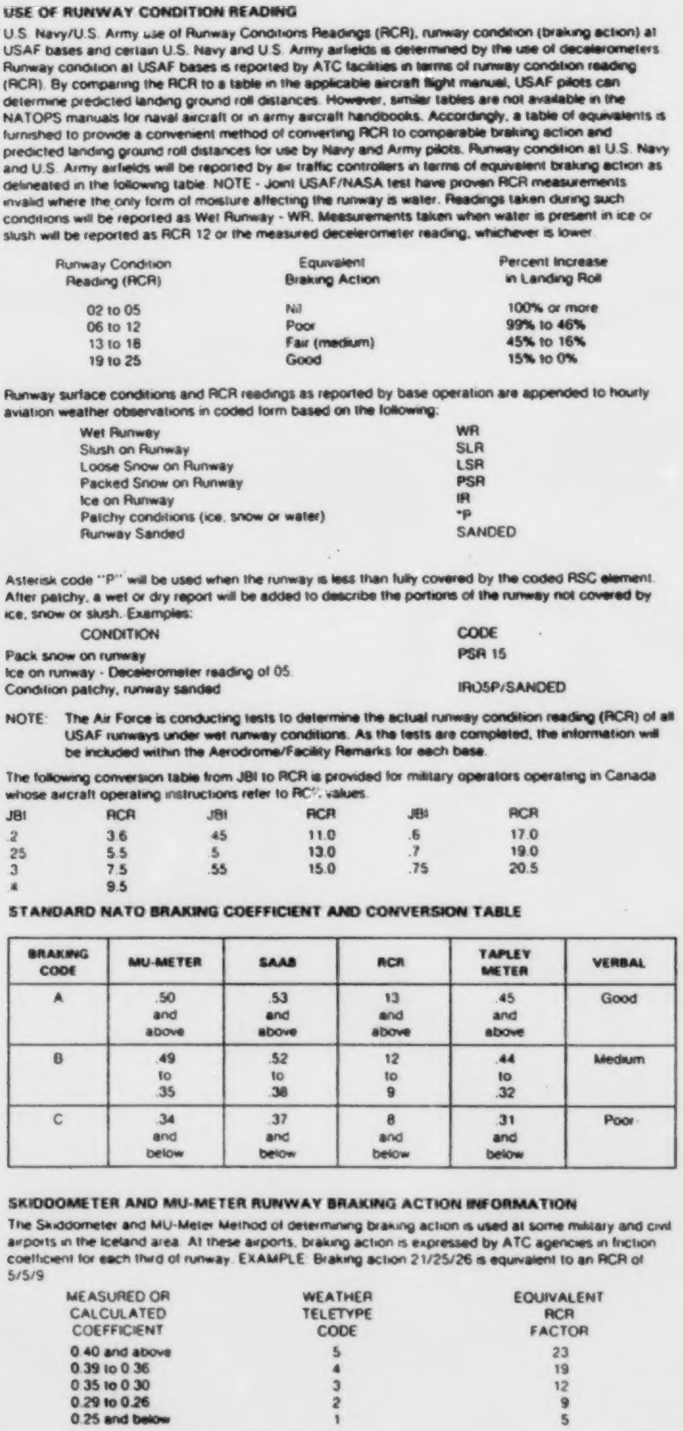
6.3.8 Airline Practices With Use Of Runway Condition Data

The status of airline guidance to pilots for take-off operating procedures from contaminated runways has not been collected during the conduct of this study. However, some information has been forthcoming from the airline community and is presented here to illustrate a significant variation in airline practices, but also to demonstrate that inspite of the generally low confidence in friction testing machines because of machine to machine unsatisfactory correlation, and also poor machine to aeroplane correlation, there is reasonable acceptance of the ICAO SARPS data in Figure 3.4 for snow and ice covered runways.

There is some indication that for wet runways the NATO Standard in Figure 6.6 is considered representative of appropriate data.

However, most airlines provide guidance for operations from contaminated runways and the decision as to "best practice" is left to the crew of the aeroplane. Exceptions exist for airlines of the U.K., Sweden, Japan, France, and possibly airlines of the other JAA member countries, where the airline operations manuals require a means to adjust take-off performance for operations on contaminated runways. The acceptable means of compliance may take various forms such as scheduled distances for dry, wet, snow/ice covered surfaces, or reductions in take off weight correlated to wet, snow, ice conditions.

Limiting depths for snow, water, and slush are common place and have been widely accepted for twenty years by airlines, airports, and manufacturers.



USE OF RUNWAY CONDITION READING

U.S. Navy/U.S. Army use of Runway Conditions Readings (RCR), runway condition (braking action) at USAF bases and certain U.S. Navy and U.S. Army airfields is determined by the use of decelerometers. Runway condition at USAF bases is reported by ATC facilities in terms of runway condition reading (RCR). By comparing the RCR to a table in the applicable aircraft flight manual, USAF pilots can determine predicted landing ground roll distances. However, similar tables are not available in the NATOPS manuals for naval aircraft or in army aircraft handbooks. Accordingly, a table of equivalents is furnished to provide a convenient method of converting RCR to comparable braking action and predicted landing ground roll distances for use by Navy and Army pilots. Runway condition at U.S. Navy and U.S. Army airfields will be reported by air traffic controllers in terms of equivalent braking action as delineated in the following table. NOTE - Joint USAF/NASA test have proven RCR measurements invalid where the only form of moisture affecting the runway is water. Readings taken during such conditions will be reported as Wet Runway - WR. Measurements taken when water is present in ice or slush will be reported as RCR 12 or the measured decelerometer reading, whichever is lower.

Runway Condition Reading (RCR)	Equivalent Braking Action	Percent Increase in Landing Roll
02 to 05	Nil	100% or more
06 to 12	Poor	99% to 46%
13 to 18	Fair (medium)	45% to 16%
19 to 25	Good	15% to 0%

Runway surface conditions and RCR readings as reported by base operation are appended to hourly aviation weather observations in coded form based on the following:

Wet Runway	WR
Slush on Runway	SLR
Loose Snow on Runway	LSR
Packed Snow on Runway	PSR
Ice on Runway	IR
Patchy conditions (ice, snow or water)	*P
Runway Sanded	SANDED

Asterisk code "P" will be used when the runway is less than fully covered by the coded RSC element. After patchy, a wet or dry report will be added to describe the portions of the runway not covered by ice, snow or slush. Examples:

CONDITION	CODE
Pack snow on runway	PSR 15
Ice on runway - Decelerometer reading of 05.	
Condition patchy, runway sanded	IR05P/SANDED

NOTE: The Air Force is conducting tests to determine the actual runway condition reading (RCR) of all USAF runways under wet runway conditions. As the tests are completed, the information will be included within the Aerodrome/Facility Remarks for each base.

The following conversion table from JBI to RCR is provided for military operators operating in Canada whose aircraft operating instructions refer to RCR values.

JBI	RCR	JBI	RCR	JBI	RCR
.2	3.6	45	11.0	.6	17.0
25	5.5	.5	13.0	.7	19.0
.3	7.5	.55	15.0	.75	20.5
.4	9.5				

STANDARD NATO BRAKING COEFFICIENT AND CONVERSION TABLE

BRAKING CODE	MU-METER	SAAB	RCR	TAPLEY METER	VERBAL
A	.50 and above	.53 and above	13 and above	.45 and above	Good
B	.49 to .35	.52 to .38	12 to 9	.44 to .32	Medium
C	.34 and below	.37 and below	8 and below	.31 and below	Poor

SKIDDOMETER AND MU-METER RUNWAY BRAKING ACTION INFORMATION

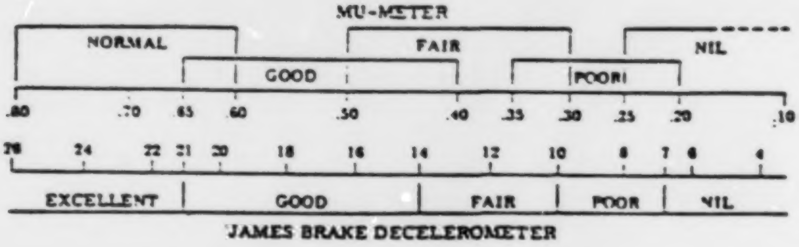
The Skiddometer and MU-Meter Method of determining braking action is used at some military and civil airports in the Iceland area. At these airports, braking action is expressed by ATC agencies in friction coefficient for each third of runway. EXAMPLE: Braking action 21/25/26 is equivalent to an RCR of 5/5/9

MEASURED OR CALCULATED COEFFICIENT	WEATHER TELETYPE CODE	EQUIVALENT RCR FACTOR
0.40 and above	5	23
0.39 to 0.36	4	19
0.35 to 0.30	3	12
0.29 to 0.26	2	9
0.25 and below	1	5

Figure 6.6 Military Runway Condition Readings

Source: Canadian VFR Supplement, Pages E14, E15

Specific examples of airline practices are provided Figures 6.7 to 6.9.



NORMAL - Max energy stops possible with little deterioration in certified stopping distance.

GOOD - More braking is available than will be used in an average airline type deceleration. If a max energy stop were attempted, some distance in excess of certified stopping distance would be expected.

FAIR - Sufficient braking and cornering force is available for a well-flown approach and landing using light braking. However, over-speed or long touchdown would result in an extremely low safety factor depending on runway length and X-wind component. Careful planning and good judgment are required.

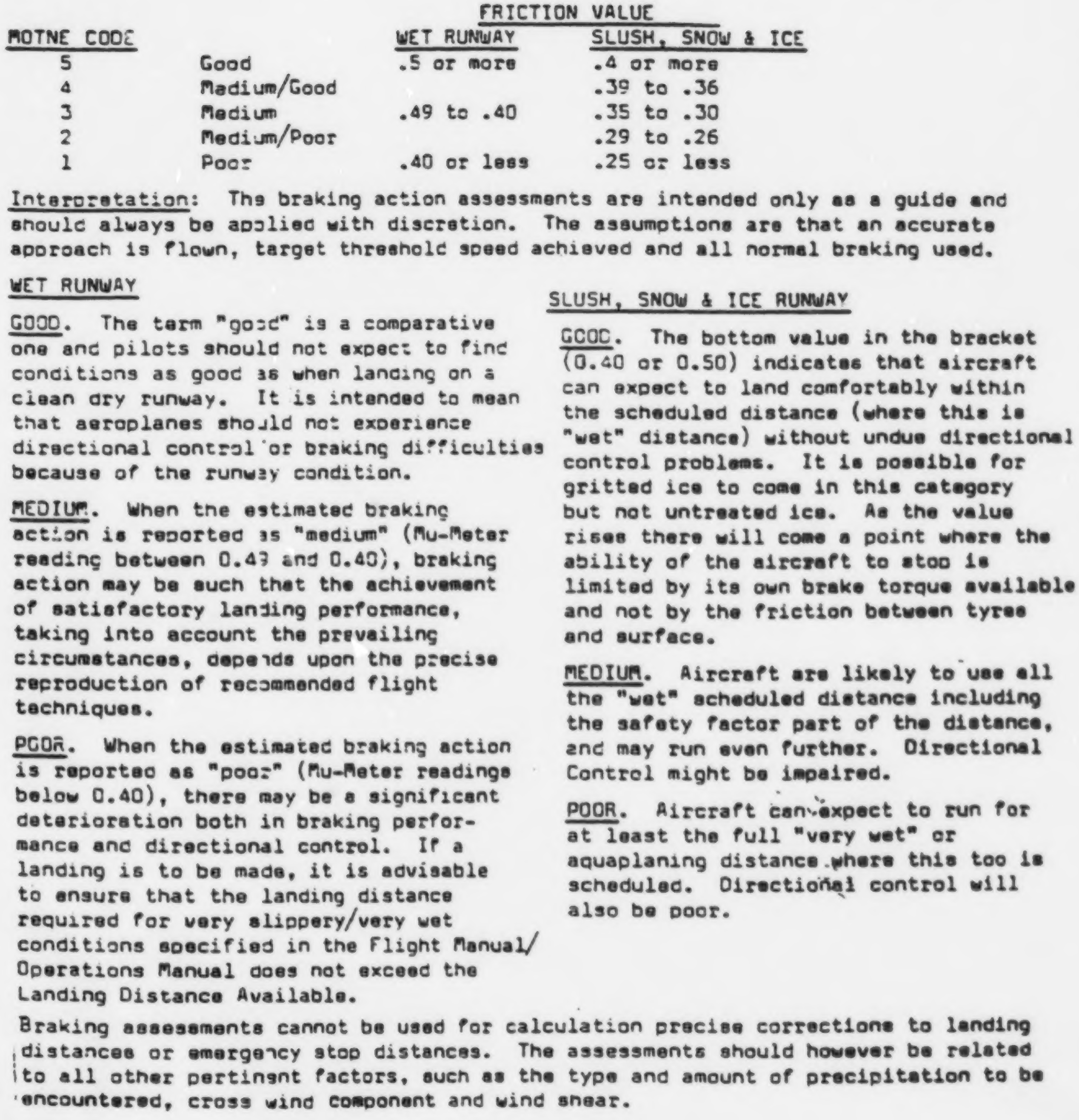
POOR - Very careful planning, judgment and execution are absolutely essential. X-wind becomes a "priority one" consideration. While a safe and successful approach, landing and stop can be accomplished if all factors are favorable, there is little room for error. Care must be exercised in every facet of the operation and a very careful evaluation of all existing conditions is necessary.

Figure 6.7 First Example of Typical Airline Guidance Information Provide To Pilots

Source: Confidential

In summary, the selection of runway friction data appropriate to a take-off on a contaminated runway remains difficult unless the friction measuring machine data and the aeroplane braking action data have been demonstrated to have good or acceptable correlation which means that measured data transmitted to the pilot must be in a form acceptable to his company operations manual and should be translatable into aeroplane braking effectiveness for accelerate stop performance.

It is interesting to note that it is relatively easier for military operations to successfully match measured data and runway condition to take-off performance estimates because all the data is under the control of a common authority in the military.



MOTNE CODE		FRICTION VALUE WET RUNWAY	SLUSH, SNOW & ICE
5	Good	.5 or more	.4 or more
4	Medium/Good		.39 to .36
3	Medium	.49 to .40	.35 to .30
2	Medium/Poor		.29 to .26
1	Poor	.40 or less	.25 or less

Interpretation: The braking action assessments are intended only as a guide and should always be applied with discretion. The assumptions are that an accurate approach is flown, target threshold speed achieved and all normal braking used.

WET RUNWAY

GOOD. The term "good" is a comparative one and pilots should not expect to find conditions as good as when landing on a clean dry runway. It is intended to mean that aeroplanes should not experience directional control or braking difficulties because of the runway condition.

MEDIUM. When the estimated braking action is reported as "medium" (Mu-Meter reading between 0.49 and 0.40), braking action may be such that the achievement of satisfactory landing performance, taking into account the prevailing circumstances, depends upon the precise reproduction of recommended flight techniques.

POOR. When the estimated braking action is reported as "poor" (Mu-Meter readings below 0.40), there may be a significant deterioration both in braking performance and directional control. If a landing is to be made, it is advisable to ensure that the landing distance required for very slippery/very wet conditions specified in the Flight Manual/Operations Manual does not exceed the Landing Distance Available.

SLUSH, SNOW & ICE RUNWAY

GOOD. The bottom value in the bracket (0.40 or 0.50) indicates that aircraft can expect to land comfortably within the scheduled distance (where this is "wet" distance) without undue directional control problems. It is possible for gritted ice to come in this category but not untreated ice. As the value rises there will come a point where the ability of the aircraft to stop is limited by its own brake torque available and not by the friction between tyres and surface.

MEDIUM. Aircraft are likely to use all the "wet" scheduled distance including the safety factor part of the distance, and may run even further. Directional Control might be impaired.

POOR. Aircraft can expect to run for at least the full "very wet" or aquaplaning distance where this too is scheduled. Directional control will also be poor.

Braking assessments cannot be used for calculation precise corrections to landing distances or emergency stop distances. The assessments should however be related to all other pertinent factors, such as the type and amount of precipitation to be encountered, cross wind component and wind shear.

Figure 6.8 Second Example of Typical Airline Guidance Information To Pilots

Source: Confidential

Mu Meter Reading	Effect on Stopping Distance
greater than a datum value	No effect
datum value	
less than datum value	increase distance by x meters per 0.01 below datum Mu Meter reading

Figure 6.9 Third Example Typical Airline Guidance To Pilots

Source: Confidential

It is clear that until ICAO is successful in increasing the scope of standards for contaminated runway flight operations which would require friction measurements which translate into reliable aeroplane braking effectiveness values, the best that can be achieved for civil flight operations is agreement on a code of runway conditions which will be useful in correlation to aeroplane flight manual performance for the purpose of adjusting take-off performance for dry/contaminated ratios.

A sample of the possible code which could be developed in combination with the runway statistical calibration discussed in Section 3, is presented in Figure 6.10. The ground test vehicle chosen for the example is the MU-meter, but could easily have been others which operate on the rolling wheel principle, and which Ref. 56 does treat similarly for wet conditions in Table VI.

The ICAO Doc. 9137 Figure 5.1 data was selected as the range for contamination due to snow and ice and the Ref. 56 data was selected for dry and wet (under 3mm) conditions.

The calculation of the effective aircraft μ, μeff was based upon Ref. 56 methodology for predicting μeff from ground vehicle measurements.

The verbal description of braking conditions was adapted from ICAO Figure 5.1, SNOWTAM, airline and military codes.

It can be seen in Figure 6.10 that the JAR/Airbus code values of $\mu/2$ and $\mu/4$ are bracketed by the MUM Code corresponding ranges of values.

It is conceivable that in practice the MUM Code used to predict take-off performance could be adjusted on the basis of the runway (expected to be used for take-off) measured friction adjusted by the statistical calibration data for the contamination condition. This means that the value for the MUM Code in Figure 6.10 would correspond to the MU-meter adjusted measured friction value.

Description of Runway Condition	Code for Stop Dist (SD) from JAR/AIRBUS	Code Calculated From Mu-Meter Typical Measurements			Verbal Description Braking
		μMUM	μeff	MUM Code	
Dry	μdry	Over 0.75	0.50 (Ref. 56 Table A2 & A3)		Good
Wet (under 3mm)	$\frac{\mu dry}{2}$	0.55 to 0.75	0.155 to 0.3 (Ref. 56 Table VI 150 psi)	$\frac{\mu dry}{1.7 \text{ to } 3.2}$	Good to Medium
Contaminated (Water, snow and ice*)	$\frac{\mu dry}{4}$	0.17 to 0.47 (ICAO Fig. 5.1 Doc 9137)	0.055 to 0.25 (Ref. 56 Equation 5)	$\frac{\mu dry}{2 \text{ to } 9.1}$	Medium to Poor

* ICE = if glare ice it would likely be unreliable to measure friction and not suitable for take-off

μMUM = μ value measured by Mμ-Meter

Figure 6.10 Sample Stop Distance Code for MU-Meter

The Mu-meter adjusted measured friction value should be the mean value from the statistical calibration curve for the depicted runway which is illustrated in the example in Figure 6.11. The range of values is identical with the range of values of μMUM in Figure 6.10 for the appropriate runway surface condition.

Figure 6.12 illustrates the values of μeff for the runway depicted in Figures 6.10, 6.11, and 6.13 where μeff is the estimated effective braking friction coefficient for an aeroplane for the depicted runway.

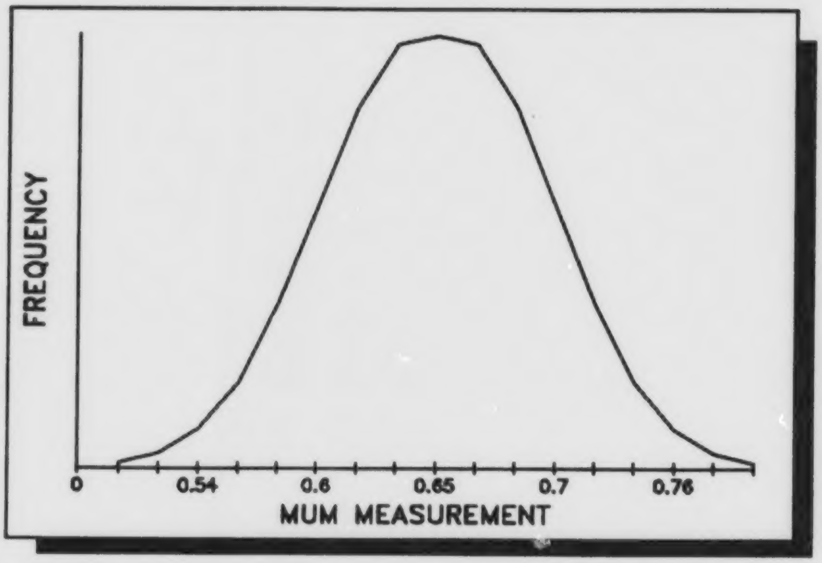


Figure 6.11 Typical Runway Calibration Curve for Specific Runway Surface Condition (Wet in This Example)

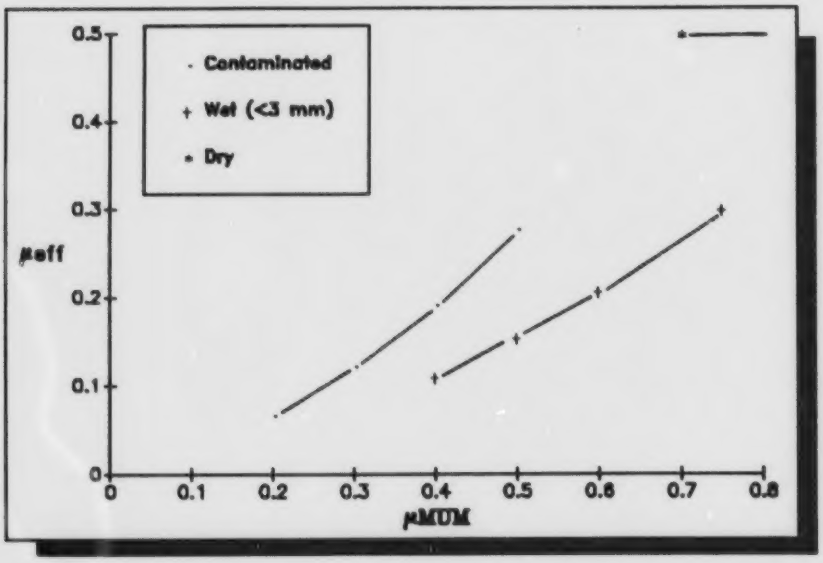


Figure 6.12 Estimated Effective Braking Coefficient, μeff, Relationship to Measured μMUM from Figure 6.10

Figure 6.13 is the relationship between the ratio of aeroplane stopping distances for wet and contaminated surfaces and the dry surface, versus the MUM measured friction. The stopping distance ratio is presented as the MUM Code from Figure 6.10, and as 1/μMUM, similar to that of Figure 6.14. Also, data for the B747-100, which were obtained from Section 4 Take-off Performance, have been superimposed.

The comparison of Figures 6.13 and 6.14 affords the opportunity to relate the sample code in Figure 6.10 to data from B727 trials and UTIAS simulator data for the B747-100. The comparison is encouraging and supports the prospects of developing a means to utilize more representative estimated effective braking friction than that of μdry/2 or μdry/4 for specific runway take-off performance accountability.

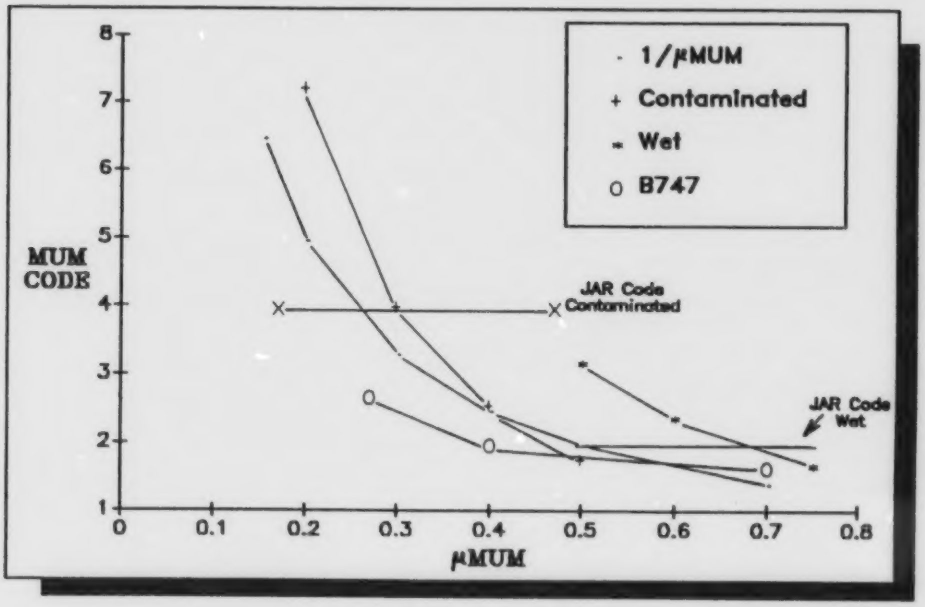


Figure 6.13 Ratio of Stopping Distance on Wet and Contaminated Surfaces to Stopping Distance on Dry Surfaces versus the MUM Measured Friction, μMUM

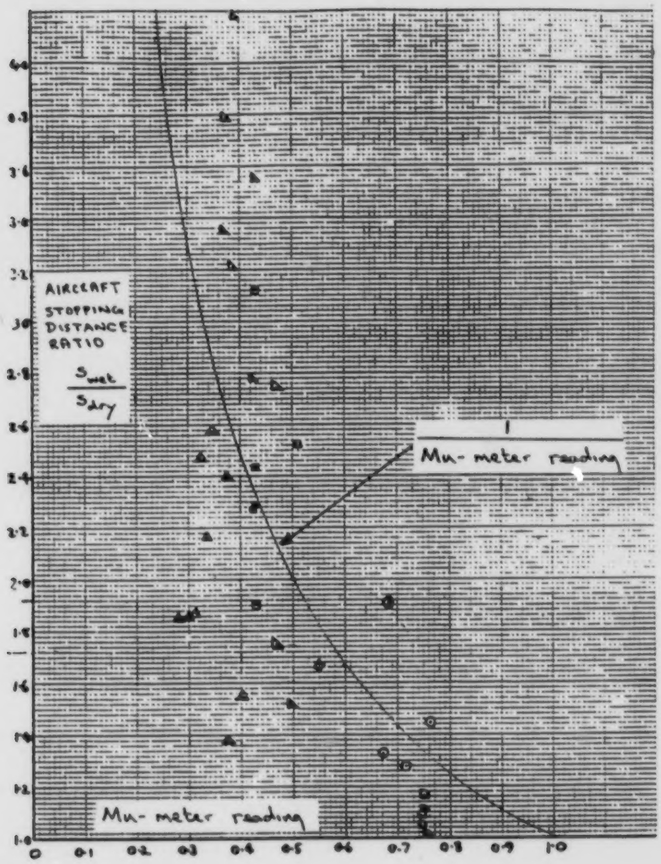


Figure 6.14 Relationship Between Aircraft Stopping Distance Ratio and Ground Vehicle

Source: Confidential

7. COUNTER MEASURES

7.1 Introduction

Counter measures are intended to be effective under any combination of tire condition, runway surface condition, and runway contaminant condition which are considered reasonable for successful aeroplane take-off or accelerated stop.

Thus, for purposes of this report, the contribution of tires, runway surface texture, and runway contaminant reduction or removal are considered to be dependent upon standard maintenance good practices and should not be considered as counter measures.

Accordingly, a counter measure should be considered as a means to predict performance under known conditions, or as a means to monitor performance during the take-off so that appropriate action may be taken by the pilot to abort or continue flight. There are circumstances where both the prediction and monitoring counter measures are essential to safety.

The predictive approach to avoiding a take-off accident relies upon take-off performance accountability having been demonstrated by the manufacturer and by providing the pilot with the procedure in the AFM to calculate the performance under all reasonable acceptable weather and runway conditions.

The monitoring approach to avoiding a take-off accident consists of providing a means for the pilot to monitor acceleration or velocity versus position along the runway so that V_1 is reached with sufficient runway remaining to conduct an accelerate-stop.

In either case of prediction or monitoring, the contaminant is a major factor due to displacement and impingement on the aeroplane or due to it causing reduced runway friction.

Although prior to V_1 the rolling friction of the tires is less on contaminated runway than on a dry runway due to the decrease in runway friction, the contaminant drag on snow and water covered runways due to displacement and impingement far exceeds the decreased rolling friction.

After V_1 the braking friction would be less than for a dry runway due to the contaminant and there would be an element of displacement and impingement drag, but it would be much less than the braking action due to wheel braking and reverse thrust.

The predictive approach requires the TOD and ASD to be predicted accounting for the various effects of the contaminant. The aeroplane is only dispatched when both TOD and ASD are equal to or less than the available runway. The monitoring approach requires the capability to compare the actual take-off performance with the predicted performance at any point during take-off to enable the pilot to decide whether to continue the take-off or to abort.

It is possible to use conservative friction values to ensure the aeroplane take-off weight will not upset the TOD and ASD requirement, but conservation is not usually cost effective. To be cost effective it would be reasonable to use less conservatism is predicting take-off performance which implies less conservatism in the friction values and reliance on a take-off monitoring system.

There are other approaches to counter measures involving alternative methods to wheel braking and reverse thrust for decelerating the aircraft, such as tail chutes and arresting devices.

This Section will discuss counter measures involving:

- take-off performance accountability
- take-off monitoring systems
- deceleration systems

7.2 Take-off Performance Accountability

As already stated in Section 2.1, at this time Transport Canada does not require the take-off performance of large civil jet transports to be adjusted for the effects of runway contamination either from an airworthiness or operational point of view. However, over the past two years the Director of Airworthiness has been observing the discussions between the USA FAA and the European JAA on the subject with the objective of ascertaining the best direction in which Canadian airworthiness requirements should be directed. Although Transport Canada, as a consequence of the Dubin Commission on Safety, has adopted the FAA design airworthiness standards as the basis for Canadian standards, to-date no such direction has been followed in airworthiness operational matters. In any case, the FAA do not have any operational or airworthiness standards for contaminated runway take-off performance in this area against which Canada could make a judgement.

Recently at a joint meeting of the FAA and JAA, it is understood that the FAA has decided to introduce a wet runway condition for take-off performance determination into the flight manual of newly designed aeroplanes subject to the NPRM system; also it is understood that the FAA will provide revised advisory material in AC 91-6 dealing with information for operators on the subject of operating from contaminated runways.

Meanwhile the individual European countries and Japan have taken positive steps over the years to introduce regulations on the subject of contamination, which in 1988 resulted in JAA issuing a revision to JAR 25 and issuing an Acceptable Means of Compliance (ACJ) for take-off performance accountability during contaminated runway conditions.

Since Canada does not have any requirements for take-off or landing performance from contaminated runways, it would seem that one counter measure that Canada could use would be to adopt the JAR approach. This approach would also be consistent in that the weather conditions throughout Europe, including Norway and Sweden, are similar to Canada. Also this approach would make available, almost immediately, take-off information for contaminated runways on such aeroplanes as the Airbus 320 and the BA 146 (See Sections 4.3.2 and 4.3.5)

Should Canada adopt the airworthiness approach defined by JAR 25 and AMJ 25C1591, then the approach would be somewhat different than that to which Canadian operators are currently accustomed, and the question of retroactivity of such an approach to older aeroplanes would require some thought. The acceptable means of compliance for wet and contaminated runways with the JAR 25 approach is given below.

1) If the runway is wet (well soaked but without significant areas of standing water) the following would apply (Ref. 19).

3. Acceptable Means of Compliance

3.1 General Conditions

Take-off performance information for wet runways and take-off landing performance information for runways contaminated by standing water, slush, loose snow, compacted snow or ice should be determined in accordance with the following assumptions:

3.2 Take-off Performance Information for Wet Runways

3.2.1 The supplementary performance information required by JAR 25X1591 should include accelerate-stop distance, take-off distance and take-off run appropriate to a wet runway, defined as follows:

a. The accelerate-stop distance on a wet runway is the greater of the following:

i. The sum of the distances necessary to -

A Accelerate the aeroplane with all engines operating from a standing start to V_{EF} corresponding to V_{STOP};

B Accelerate the aeroplane from V_{EF} to V_{STOP} and continue the acceleration for 2.0 seconds after V_{STOP} is reached, assuming the critical engine fails at V_{EF}; and

C Come to a full stop on a wet runway from the point reached at the end of the acceleration period prescribed in sub-paragraph (a) (i) (B), assuming that the pilot does not apply any means of retarding the aeroplane until that point is reached and that the critical engine is still inoperative.

ii. The sum of the distances necessary to -

A Accelerate the aeroplane from a standing start to V_{STOP} and continue the acceleration for 2.0 seconds after V_{STOP} is reached, with all engines operating; and

B Come to a full stop on a wet runway from the point reached at the end of the acceleration period prescribed in sub-paragraph (a) (ii) (A), assuming that the pilot does not apply any means of retarding the aeroplane until that point is reached and that all engines are still operating.

b. The take-off distance on a wet runway is the greater of the following:

i. The horizontal distance along the take-off path from the start of the take-off to the point at which the aeroplane is 15 ft above the take-off surface, achieved in manner consistent with the achievement of V_2 before reaching 35 ft above the take-off surface, as determined under JAR 25.111 and assuming that the critical engine fails at V_{EF} corresponding to V_{GO}.

ii. 115% of the horizontal distance along the take-off path, with all engines operating, from the start of the take-off to the point at which the aeroplane is 35 ft above the take-off surface, as determined by a procedure consistent with JAR 25.111 (See ACJ 25.113 (a) (2)).

c. The take-off run on a wet runway is the greater of the following:

i. The horizontal distance along the take-off path from the start of the take-off to a point at which V_{LOF} is reached, as determined under JAR 25.111 and assuming that the critical engine fails at V_{EF} corresponding to V_{GO}.

ii. 115% of the horizontal distance along the take-off path, with all engines operating, from the start of the take-off to the point equidistant between the point at which V_{LOF} is reached and the point at which the aeroplane is 35 ft above the take-off surface, as determined by a procedure consistent with JAR 25.111 (See ACJ 25.113 (a) (2)).

NOTE: V_{STOP} is the highest decision speed from which the aeroplane can stop within the accelerate-stop distance available. V_{GO} is the lowest decision speed from which a continued take-off is possible within the take-off distance available.

3.2.2 Means other than wheel brakes may be used to determine the accelerate-stop distance if that means -

a. Is safe and reliable;
b. Is used so that consistent results can be expected under normal operating conditions; and
c. Is such that exceptional skill is not required to control the aeroplane.

2) If the runway is contaminated by standing water, slush, loose snow, or compacted snow/ice the take-off requirements would be the same as for wet runway but modified as follows:

3.3 Take-off Performance Information for Contaminated Runways

3.3.1 The supplementary performance information required by JAR 25X1591 should include accelerate-stop distance, take-off distance and take-off run appropriate to the relevant contaminant, derived in accordance with the general provisions of paragraph 3.2.1.

a. Standing water, slush or loose snow

Assumptions relating to wheel-braking coefficient of friction should be those of paragraph 3.5 and assumptions relating to precipitation drag should be those of paragraph 4.

b. Compacted snow or ice

Assumptions relating to wheel-braking coefficient of friction should be those of paragraph 3.5.

3.3.2 In establishing accelerate-stop distance, performance credit for reverse thrust may be assumed, subject to compliance with the general provisions of paragraph 3.2.2 being shown.

It should be noted that the terminology of V_{GO} or V_{STOP} is similar to the use of V_1 as a decision speed for the determination of the ASD and TOD.

If the JAR approach was adopted, the V_1 speed may be reduced thereby reducing the exposure of engine failure leading to V_1 and increasing the runway available to stop while at the same time increasing the take-off distance. However, the TOD is

determined to a screen height of only 15′ rather than 35′ thereby reducing the potential impact of this requirement. The minimum V_1 speed chosen must still meet the requirement of not being below V_{mcg} for the chosen conditions.
In the case of the simulator tests carried out as described in Section 4, one test was carried out at a V_1 equal to V_{mcg} under wet conditions and the TOD was determined. The results are as follows:

Boeing 747 simulator,

Wt = 530000 lbs, H_p = 3500 ft, OAT = 27^0 C

TOD = 8371′ over a 15′ screen
TOD = 8768′ over a 35′ screen

7.3 Take-off Performance Monitoring Systems

Ref. 41 (1984) states that the accident rates in the take-off phase have remained relatively constant for many years whereas rates in other phases of flight had decreased and suggests that the vast majority of take-off accidents could have been prevented if a suitable cockpit system to monitor the take-off had been available. Research into pilot monitoring of aeroplane take-off performance, centres around the presentation of actual take-off performance versus that which was predicted using the AFM take-off performance methodology.

The concept of a take-off performance monitoring system is not new and perhaps one of the earliest types was based on the checking of airspeed at a pre-determined point along the runway. Another simple approach was to check the time taken to acquire a certain airspeed or to present to the crew a Go/No Go indicator based on longitudinal acceleration (Ref. 38).

When considering a take-off monitoring system the prime parameters are as indicated in Section 4:
velocity/acceleration (thrust less drag), type and depth of runway contamination, runway friction, aeroplane wing lift configuration, wind speed and direction, airport altitude and temperature, and weight. The monitoring system must be provided with data on how the aeroplane is expected to perform

under the given set of environmental conditions and the selected V_1 and V_R. Then, by sensing the changes in variables during the actual take-off, the monitoring system determines the final take-off performance and presents a Go/No Go indication in the cockpit. The form of presentation is one of choice since a wide variety of possibilities exist.

The above system, however developed and its Go/No Go results presented, must be reliable and as accurate as any other information that the crew require to ensure a safe operation.

One study which has been in process since 1986 (Ref's 36 & 40) has resulted in the development of a monitoring system that takes into account all the above considerations and presents the flight crew with a read out in the form shown in Figure 7.1. The system is called the TOPMS (Take-off Performance Monitoring System) and is currently installed in NASA's 737

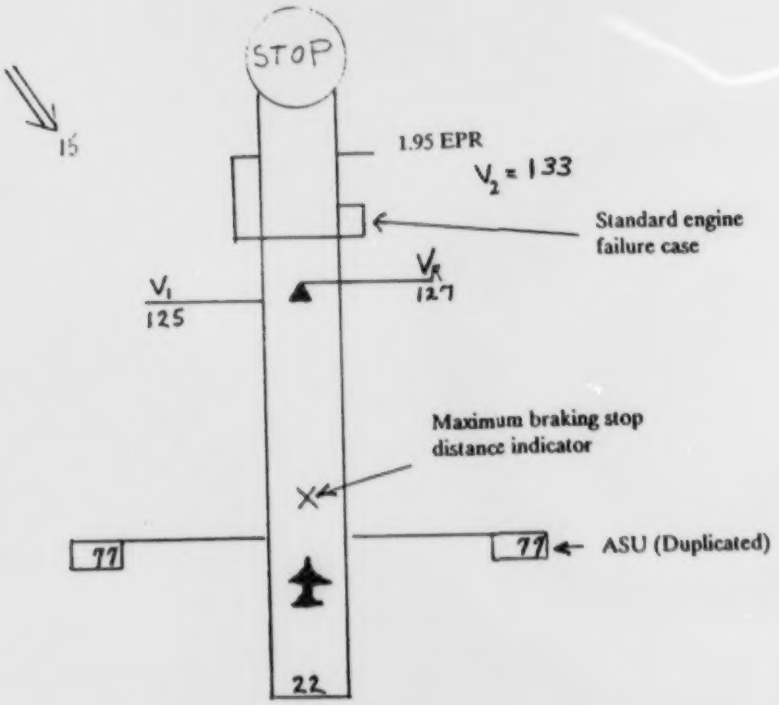

STOP
15
1.95 EPR
V2 = 133
Standard engine failure case
V1 125
VR 127
Maximum braking stop distance indicator
77
77
ASU (Duplicated)
22

Figure 7.1 Example of Screen Display for NASA Take-off Performance Monitoring System

Source: Ref. 36, Page 43

flight simulator. The system uses a data base of the aeroplane's performance to calculate the position along the runway at which it will achieve the V_1 and V_R speeds and the furthest point at which the aeroplane can rotate and still clear the 35' screen. In this proposed system the flight crew enter the aeroplane's center of gravity, weight, flap setting, runway direction, altitude, temperature, wind speed and direction and runway rolling friction and the computer calculates V_1 and V_R and ground roll limits. The crew then enters the runway length and the display shows where the two speeds are located along the runway. During the take-off, the system continually displays the location of the aeroplane on the runway and the projected distance to V_R and the distance required to stop the aeroplane. The speeds are chosen for a balanced field length.

The system, which is probably as advanced as any in existence for civil use, was recently evaluated by 30 USA airline pilots who indicated that questions such as system accuracy and reliability, compatibility with other CRT displays and the systems ability to accommodate operations restrictions must be answered before it could be considered for operational use.

The system outlined in Ref. 40 and others, basically use derived aeroplane accelerations to conclude whether the take-off is a Go/No Go situation. However, one aspect of such systems, as indicated in the simulator tests carried out on the Boeing 747 described in Section 2, is the sensitivity of the final decision to the accuracy to which the acceleration is determined.

As can be seen from Figure 7.2, the maximum difference in acceleration between dry runway at 27^0C and slush covered runway at -2^0C is 0.5 ft/s^2 or 10%, but the deceleration required to stop the aeroplane in a given length is different by 5.5 ft/s^2 or 50%. The resulting ASD's differ by 3352 feet or 27% and the TOD's differ by 180 feet or less than 2%.

These two results are very idealistic when compared to the real world, especially when determining the runway conditions in terms of friction values and contaminant depth under adverse weather conditions. In actual operating conditions the runway friction will not be uniform throughout the take-off and neither will the depth or specific gravity of the contaminant. Therefore, the ability to sense relatively small changes in acceleration in a meaningful manner during the early part of the take-off roll will present a complicated task. However, at the present time in Canada and in the USA, the crews are not provided with AFM/Operational information with respect to the take-off performance accountability for contaminated runways.

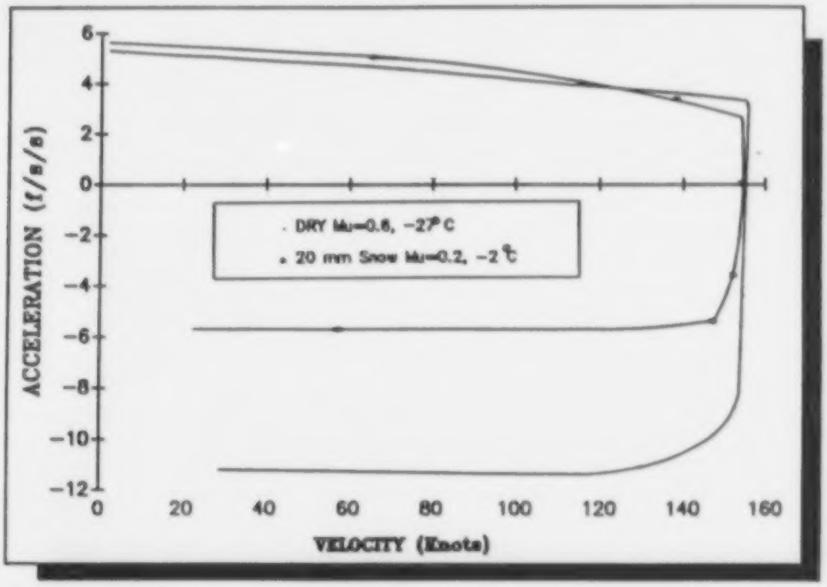


Figure 7.2 Acceleration versus Speed for B747 on a Dry Runway At 27^{0}C and on a Slush Covered Runway at -2^{0}C

Data source: UTIAS simulator (Appendix D)

7.4 Deceleration Systems

7.4.1 Reverse Thrust and Emergency Brake Parachute

Water and other contaminants on the runway reduce the friction between the aircraft tires and the runway and this increases the distance required for the aircraft to stop. Braking mechanisms which do not rely on tire-runway friction would not be affected by any runway contamination.

Engine reverse thrust is an effective form of braking in these situations and can increase the deceleration rate by about 0.1 g. Reverse thrust increases the deceleration rate above that provided by maximum anti-skid braking for the B737 by approximately 20% on a dry runway, 34% on a wet runway and by almost double on a water covered runway (see Appendix E.8). However, if an engine failure has occurred, the braking force provided by reverse thrust is asymmetric and this reduces the controllability of the aircraft. Runway contamination compounds this problem because the side friction on the tires becomes insufficient to stop the aircraft drifting sidewards (described in Section 4.2.5). The airworthiness regulations (discussed in Section 7.2.2) provides for the use of reverse thrust for aborted take-offs on wet and contaminated runways subject to meeting certain conditions.

An emergency brake parachute is an alternative form of air brake which works effectively on low friction runways. Parachutes can increase the deceleration rate by 0.2 g (8 ft/s/s) at high speeds, but the rate decreases with the square of the velocity. The controllability problems are less using a parachute than using reverse thrust as the chute exerts a retarding force at the center of the back of the aircraft. However, crosswinds will pull the parachute off centre and place a sidewards force on the aircraft which, on a contaminated runway, may be difficult to control. Parachutes have been used in many fighter aircraft and some versions of the Gates Lear jet, but are not currently used in any large commercial jet aircraft.

As a countermeasure for contaminated runways, an emergency parachute would only be used for aborted take-offs from high speeds. The parachutes would not be used for routine stops, but would provide an added backup for any emergency stopping situations. The additional braking force provided by the parachute could be included in the take-off performance calculations for wet or contaminated runways provided it met all appropriate airworthiness requirements.

7.4.2 Arrestors

Arrestors for decreasing aeroplane speeds in overrun areas can significantly decrease the risks associated with aborted take-offs. A cable type arrestor which catches a hook attached to the undercarriage of the aeroplane has been used with a number of military aircraft.

Ref. 53 (1988) investigated the feasibility of using a foam arrestor bed at JFK International Airport and found that such an arrestor design is feasible. It was shown that aircraft overrunning the runway could be safely stopped at exit speeds up to 80 knots for 100,000 lbs aircraft and exit speeds up to 60 knots for 820,000 lbs aircraft. The performance of the arrestor was shown to be superior to a paved 1,000 foot overrun area, particularly when braking is not effective and reverse thrust is not available. Passenger evacuation in the event of an accident should be no worse than under present conditions. The cost of the arrestor was estimated to be less than one-tenth the value of the potential damage to one aircraft that can occur as the result of an overrun ending in the water hazard at JFK Airport.

7.4.3 Flat Outrun Area

The risks associated with contaminated runway take-off accidents can be reduced by either reducing the probability of their occurrence or by reducing the severity of the accident. The counter measures discussed above deal with reducing the chance of an accident occurring.

The severity of an accident can be reduced by improving the crash-worthiness of the aircraft and/or by improving the area beyond and beside the runway. The crash-worthiness of aircraft has improved considerably over the last 20 years with the use of fire retardant fabrics, stronger seats, etc. and research is continuing in this area. The low fatality rate in take-off accidents in recent years is testimony to the improved crashworthiness.

Alternatively, the severity of the accident could be reduced by improvements to the area beyond and beside the runway such as ensuring the area is flat smooth land with no ditches or embankments and is free of any large obstacles which would cause an aircraft serious damage.

As discussed in Section 2, few accidents involve fatalities when the aircraft overruns the runway onto flat terrain and, in these cases, fire is the greatest threat to safety. However, fire occurred in only 11% of aborted take-off accidents on wet or contaminated runways since 1970. Less than 0.3% of persons onboard during aborted take-off accidents on wet or contaminated runways were killed when the aircraft stopped on flat terrain, but 6.5% were killed when the aircraft ran into a ditch, embankment, other obstacle or water. The risk is approximately 25 times greater in the latter case.

Thus, fire is a relatively uncommon occurrence for aborted take-off accidents on wet or contaminated runways and, provided the aircraft runs onto flat terrain, the accident severity is usually low. A possible counter measure which could significantly improve safety and have a minimal effect on aircraft operations could be to make more extensive use of stopways in conjunction with the JAR 25 performance restrictions outlined in the previous section.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

8.1.1 Effect of Runway Contamination on Take-off Performance

- Take-off performance is affected on wet or contaminated runways in three ways:
  - decrease in braking effectiveness due to reduced friction between tires and runway;
  - increased drag due to the displacement of the contaminant by the tires and the impingement of the contaminant on the aircraft; and
  - reduction in the directional control of the aircraft due to reduced friction between tires and runway.
- The accelerate-stop distance is increased by approximately:

  15% on a wet runway,
  50% on a snow covered runway (typical snow depths),
  75% on a water covered (more than 3 mm or 0.1 in.) runway,
  100% or more on a treated ice covered runway.
- Take-off distances are greater on runways covered with loose snow, slush and water and are very dependent on the density and depth of contaminant; typical depths of slush and loose snow increase take-off distance by about 10%.
- The 15% safety margin for take-offs on dry runways is not sufficient to account for the greater take-off distance (with no engine failure) on runways with more than 13 mm (½ in.) of slush or 25 mm (1 in.) of loose dry snow for some aircraft types.

8.1.2 Accident Frequency and Risks

- Wet and contaminated runways have been a contributing cause in a third of the 84 accidents on take-off in first-world countries since 1970.

- Wet or contaminated runways are rarely the only cause of take-off accidents, but they reduce the margin of safety available and, as a result, accidents are more likely under those runway conditions.

- The accident risk in Canada of take-offs from wet or contaminated runways is approximately twice the risk of take-off from dry runways.

- The occurrence of fire is common in aborted take-off accidents on dry runways, but is relatively uncommon on wet or contaminated runways.

- The combination of a contaminated runway and a critical event, such as engine failure, occurring near the decision speed, V_1, pose a great threat to safety under current regulations.

- Runway conditions which significantly affect the aeroplane's take-off performance are relatively common in Canada; approximately 1 in 5 take-offs in Canada are from runways which are wet or contaminated, varying from 1 in three during the colder 5 months to 1 in 10 during the warmer 7 months.

- Snow or ice on the runway is much more common in Canada than the occurrence of slush or water (depth greater than 3 mm). During winter the runways are snow covered 10-30% of the time and ice covered 2-20% of the time.

- Engine failures and other critical events on the take-off run occur infrequently in Canada; the frequency being 1 engine failure in 76,000 take-offs and 1 other type of critical event every 40,000 take-offs, or about 6 and 12, respectively, per year in Canada.

- Accident risks on take-off are much greater on wet and contaminated runways than on dry runways, and are greater than other published acceptable aircraft accident/incident risks.

- There is a very low risk (10^{-9} to 10^{-8}) of a take-off accident due to runway condition for most departures in Canada due to the runway length required at maximum take-off weight being less than the runway length available, and take-off weight being less than the allowed maximum weight. Risks are much greater (10^{-7} to 10^{-6}) for aeroplanes departing from airports where runway length required at certified maximum take-off weight is greater than the runway length available.

- Use of reverse thrust in situations where it will not greatly effect the directional control of the aeroplane reduces the risk of serious accidents by a third.

8.1.3 Runway Condition Measurements and Reporting

- The goal of achieving universality of reporting runway braking action has been identified by the operational specialists of most experienced aviation states as being highly desirable.

- The acceptability of the Annex 15 ICAO SNOWTAM Section H (runway friction measurement or braking action) for describing runway conditions has been challenged by the JAR/Airbus Industrie decision not to accept anything other than a description of the contaminant and its depth for the accountability of aeroplane take-off performance.

- No differences have been filed against ICAO Annex 14 and Annex 15 SARPS.

- The correlation of ground vehicle measurements as identified by ICAO Fig. 5.1 Doc 9137 for snow and ice conditions has been supported by the majority of investigators at least in concept if not in terms of measurement data.

- The NASA data (Ref. 56) is the most recent (1990) report to indicate support for and improvement upon ICAO Fig. 5.1 data, and it is indicative of the need to update the ICAO Fig. 5.1.

- The 1990 NASA report (Ref. 56) includes methodology and results for correlating ground vehicle friction measurements to the aeroplane effective braking friction to an accuracy of plus or minus 0.1μ, for a significant range of test conditions for several types of aeroplanes.

- There appears to be sufficient data on the characteristics of ground test vehicles to achieve international agreement on which vehicles are best suited to specific types of runway conditions and provide more detail than now exists in ICAO Doc. 9137.

- There is strong evidence that the correlation between the friction value for a specific ground test vehicle and a given type of aeroplane, on a given runway can be demonstrated to be accurate and reliable.

- The criteria needed to make it possible for a specific ground vehicle and most aeroplanes to achieve correlation of friction data on runways which have known statistically repeatable friction values is within reach of current test establishments, and could be developed for operational use.

- The calibration of runways under various dry, wet and contaminated conditions and a range of temperatures would provide a statistical calibration record suitable for assisting in the search for universality of recording and collating reliable runway friction data.

- The search for universality could be assisted by the aeroplane developers conducting actual tests under selected contaminant conditions and utilizing one of the ground test vehicles judged by international agreement to be suited to each contaminant selected for the trials.

- Further investigative work should focus on the concepts of runway statistical calibration, ground vehicle measurement limitations for take-off performance accountability, and the refinement of Ref. 56 methods for converting ground vehicle measurements to aeroplane effective braking friction values.

8.2 Recommendations

It is recommended that the following tasks be undertaken in Phase II of the study:

(a) Obtain, or estimate, contaminated runway performance for the Boeing 737 and 727 and estimate the accident risks for those aircraft. Examine runway condition data at more airports, including small remote airports. From these and the accident risks determined in Phase I, estimate the accident risks for the whole of Canada.

(b) Determine the risk reduction, in terms of reduced fatalities, hull damage and airport disruption, of selected counter measures, including regulatory changes similar to those in JAR 25X1591.

(c) Determine the operational problems associated with, and impact of, the selected counter measures, particularly introduction of JAR 25X1591, and the experiences of other countries using the counter measure.

(d) Estimate costs of selected counter measures, including introduction of JAR 25X1591; these include take-off weight reduction, increased aircraft capital and maintenance expenditure, crew training costs, expenditure on runway maintenance and improvements, etc.

(e) Determine the relative benefit-cost relationship for the selected counter measures, and draw conclusions on those that seem the most promising from a benefit-cost perspective.

(f) Research Canada's method of establishing runway condition, including the use of ground vehicles for measuring friction, and determine if the quality and completeness of data is adequate for use with the JAR 25X1591 requirements.

(g) Undertake a pilot project to calibrate selected runways at large and small airports in Canada over a period of one year and to estimate aeroplane effective braking data as a means to prepare for the adoption of take-off accountability.

Other recommendations are:

(h) Canada should evaluate its current runway ground vehicle friction measurement procedures and runway condition reporting to comply fully with ICAO Annex 14 and Annex 15.

(i) Canada should offer to undertake with other ICAO States a cooperative project designed to achieve international agreement on the criteria needed for universality of runway friction data measurement and estimation of aeroplane effective friction codes which could lead to amendments to ICAO SARPS for take-off performance accountability.

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APPENDIX A

CONTENTS:

ICAO AIRPORT SERVICES MANUAL
(DOC 9137 - AN/898)

PART 2

PAVEMENT SURFACE CONDITIONS
2ND ADDITION - 1984

AIRPORT SERVICES MANUAL

(Doc 9137-AN/898)

Part 2

Pavement Surface Conditions

Second Edition — 1984

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AMENDMENTS

The issue of amendments is announced in the *ICAO Bulletin* and in the monthly supplements to the *Catalogue of ICAO Publications*, which holders of this publication should consult. These amendments are available free upon request.

No.	Date	Entered by
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Foreword

The provisions in Annex 14 require States to take action as necessary to remove as rapidly and completely as possible contaminants from the movement area so as to provide good friction characteristics and low rolling resistance. Further, the Annex calls for the surface of pavements to be kept clear of any loose stones or other debris that might cause damage to aircraft structures or engines, or impair the operation of aircraft systems. There is a requirement to assess the condition of the pavement whenever it has not been possible to fully clear the contaminants and to make this information available to the appropriate units at the airport. There is also a requirement to measure periodically the friction characteristics of the runway and take appropriate action whenever the friction characteristics are below a level specified by the State. The purpose of this manual is to provide assistance to States in ensuring that adequate measures are taken to overcome problems resulting from contaminants and/or debris on the movement area.

It cannot be over-emphasized that the goal of an airport authority should be the removal from the movement area of all contaminants and debris which adversely affect aircraft performance. In this regard continuing research has been directed towards improving the economy and efficiency of mechanical and chemical methods to remove contaminants from the movement area. There are, however, circumstances which justify a requirement for measurement of friction values and, therefore, the development of acceptable methods for these measurements.

The possibility of obtaining correlation between the friction values produced by different types of braking test devices has been the subject of trials and discussions for some time. In 1972 ICAO arranged for a programme for the correlation of ground equipment used to measure runway braking action.

As a result a chart showing the correlation between certain braking test devices for measurements on snow- or ice-covered surfaces was developed. No correlation has been found between the test devices for measurements on wet surfaces.

This manual includes, *inter alia*, material concerning basic factors affecting friction, correlation between braking test devices on snow- or ice-covered surfaces, description of the devices, practices for measuring and reporting friction values on snow-, ice- and water-covered surfaces, collection and dissemination of pavement surface state information, and clearance and removal of contaminants and debris from the movement area.

It is intended that the manual be kept up to date. Future editions will most likely be improved on the basis of experience gained and of comments and suggestions received from users of this manual. Therefore, readers of this manual are invited to give their views, comments and suggestions on this edition. These should be directed to the Secretary General of ICAO.

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Chapter 1

General

Note.— The terms contaminant *and* debris *are used in this manual with the following meanings. A* contaminant *is considered to be a deposit (such as snow, slush, ice, standing water, mud, dust, sand, oil, and rubber) on an airport pavement, the effect of which is detrimental to the friction characteristics of the pavement surface.* Debris *is considered to be a fragment of loose material (such as sand, stone, paper, wood, metal and fragments of pavements), the effect of which is detrimental to aircraft structures or engines, or might impair the operation of aircraft systems. The effect of debris is also known as "risk of FOD (foreign object damage)".*

1.1 INTRODUCTION

1.1.1 There is a general concern over the adequacy of the available friction between the aircraft tires and the runway surface under certain operating conditions, such as when there is snow, slush, ice or water on the runway and, particularly, when the aircraft take-off or landing speeds are high. This concern is more acute for jet transport aircraft since the stopping performance of these aircraft is to a greater degree dependent on the available friction between the aircraft tires and the runway surface, their landing and take-off speeds are high and in some cases the runway length required for landing or take-off tends to be critical in relation to the runway length available.

1.1.2 A measure of the seriousness of the situation is indicated by the action of national airworthiness authorities in recommending that the landing distance requirement on a wet runway be greater than that on the same runway when it is dry. A further problem associated with the take-off of jet aircraft from a slush- or water-covered runway concerns the performance deterioration due to the precipitant drag effect as well as the airframe damage and engine combustion problem caused by impingement of these precipitants on the aircraft surfaces. Information on operational measures for dealing with the problem of taking off from slush- or water-covered runways is contained in the *Airworthiness Technical Manual* (Doc 9051-AN/896).

1.1.3 Further, it is essential that adequate information on the runway surface friction characteristics/braking action be available to the pilot in order to allow him to adjust his operating technique and apply performance corrections. If the runway is contaminated with snow or ice, a measurement of the braking action should be made and the results provided to the pilot. If the runway is contaminated with water and the runway becomes slippery when wet, the pilot should be made aware of the potential hazardous conditions.

1.1.4 Before giving detailed consideration to the need for, and methods of, assessing runway surface friction, or the precipitant drag effect due to the presence of slush or water, it cannot be over-emphasized that the goal of the airport authority should be the complete removal of all precipitants and elimination of any other conditions on the runway surface which adversely affect aircraft performance.

1.2 IMPORTANCE OF RUNWAY SURFACE FRICTION CHARACTERISTICS/BRAKING ACTION

1.2.1 Evidence from aircraft overrun and run-off incidents and accidents indicates that in many cases inadequate runway friction characteristics/braking action was the primary cause or at least a contributory factor. Aside from this safety related aspect, the regularity and efficiency of aircraft operations can become impaired significantly as a result of poor friction characteristics.

1.2.2 Adequate runway friction characteristics/braking action is mainly needed for three distinct purposes:

a) deceleration of the aircraft after landing or a rejected take-off;

b) maintenance of directional control during the ground roll on take-off or landing, in particular in the presence of cross-wind, asymmetric engine power or technical malfunctions; and
c) wheel spin-up at touchdown.

1.2.3 With respect to either aircraft braking or directional control capability, it is to be noted that an aircraft, when operating on the ground, is subject to considerable aerodynamic forces which can impair aircraft braking action or create moments about the yaw axis. They can be induced by asymmetric engine power (e.g. engine failure on take-off), asymmetric wheel brake application or by cross-wind. The result may critically affect directional stability. In each case, runway surface friction plays a vital role in counteracting these forces or moments. In the case of directional control, all aircraft are subject to specific limits regarding acceptable cross-wind components. These limits decrease as the runway surface friction decreases.

1.2.4 Reduced runway surface friction has a different significance for the landing case than for the rejected take-off case because of different operating criteria.

1.2.5 On landing, runway surface friction is particularly significant at touchdown for the spin-up of the wheels to full rotational speed. This is a most important provision for optimum operation of the electronically controlled anti-skid braking systems (installed in most current aircraft) and for obtaining the best possible steering capability. Moreover, the armed autospoilers which destroy residual lift and increase aerodynamic drag, as well as the armed autobrake systems, are only triggered when proper wheel spin-up has been obtained. It is not unusual in actual operations for spin-up to be delayed as a result of inadequate runway surface friction. In extreme cases, individual wheels may fail to spin-up at all thereby creating a potentially dangerous situation and possibly leading to tire failure.

1.2.6 Generally, the current aircraft certification performance and operating requirements are based upon the braking action provided by a clean dry runway surface, that is, when maximum braking action achievable is at a maximum for that surface. A further increment to the landing distance is usually required for the wet runway case.

1.2.7 In this respect it is to be noted that the *Airworthiness Technical Manual* recommends that the aircraft stopping distances be determined on a dry runway. It also states that the determination of stopping distances on a wet runway be by a re-evaluation of the stopping distances determined on a dry runway with the assumption that the aeroplane wheel-braking capability established in that demonstration is reduced by 50 per cent. It further indicates that the determination of stopping distances on a wet runway having the lowest surface friction characteristics that can reasonably be expected in service should be by a re-evaluation of the stopping distances determined on a dry runway with the assumption that the aeroplane wheel-braking capability established in that demonstration is reduced by 75 per cent. In this case, it is assumed that due account is taken of any reduction in the maximum reverse thrust that may be necessary to retain directional control on this low friction surface.

1.2.8 To compensate for the reduced stopping and directional control capability for adverse runway conditions (such as wet or slippery conditions) performance corrections are applied in the form of:

a) runway length increment; or
b) reduction in allowable take-off mass or landing mass; and
c) reduction of allowable cross-wind component.

1.2.9 To alleviate potential problems caused by inadequate runway surface friction there exist basically two possible approaches:

a) provision of reliable aircraft performance data for take-off and landing related to available runway surface friction/braking action; and
b) provision of adequate runway surface friction at all times and under all environmental conditions.

1.2.10 The first concept, which would only improve safety but not efficiency and regularity, has proved impracticable mainly because of:

a) the problem of determining runway friction characteristics in operationally meaningful terms; and
b) the problem of correlation between braking test devices used on the ground and aircraft stopping performance. This applies in particular to the wet runway case.

1.2.11 The second is an ideal approach and addresses specifically the wet runway. It consists essentially of specifying the minimum levels of friction characteristics for pavement design and maintenance. There is evidence that runways which have been constructed according to modern standards and which are adequately maintained provide optimum operational conditions and meet this objective. Accordingly, efforts should concentrate on developing and implementing modern standards for runway design and maintenance.

1.3 NEED FOR ASSESSMENT OF RUNWAY SURFACE CONDITIONS

1.3.1 The circumstances under which assessment of runway surface conditions is needed can be summarized as follows:

a) the dry runway case, where only infrequent measurements may be required in order to assess surface texture, wear and restoration requirements;
b) the wet runway case where only periodical measurements of the runway surface friction characteristics are required to determine that they are above a minimum acceptable level. In this context it is to be noted that serious reduction of friction coefficient can result from contamination of the runway by rubber deposits when wet;
c) the presence of a significant depth of water on the runway, in which case the need for determination of the aquaplaning tendency must be recognized;
d) the slippery runway under unusual conditions, where additional measurements should be made when such conditions occur;
e) the snow-, slush-, or ice-covered runway in which there is a requirement for current and adequate assessment of the braking conditions of the runway surface; and
f) the presence of a significant depth and horizontal extent of slush, wet snow (and even dry snow) on the runway, in which the need for determination of the precipitant drag tendency must be recognized.

Note.— Assessment of surface conditions may be needed where snow banks near the runway or taxiway are of a significant height such as to be a hazard to the aircraft the airport is intended to serve. Runways should also be calibrated when first constructed or after resurfacing to determine the wet runway surface friction characteristics.

1.3.2 The above situations may require the following approaches on the part of the airport authority:

a) for the dry and wet runway conditions corrective maintenance action should be taken whenever the runway surface characteristics are below an acceptable level. In addition, information on the potential slipperiness of the runway when wet should be made available;
b) for snow- and ice-covered runways the approach may vary depending upon the airport traffic and frequency of impaired braking action conditions. For instance:
    1) at a very busy airport or at an airport which frequently experiences the conditions of impaired braking action — adequate runway cleaning equipment and braking test devices to check the results;
    2) at a fairly busy airport which infrequently experiences the conditions of impaired braking action but where operations must continue despite an inadequacy of runway cleaning equipment — measurement of runway friction, assessment of slush precipitant drag potential and position and height of significant snow banks; and
    3) at an airport where operations can be suspended under unfavourable runway conditions but where a warning of the onset of such conditions is required — measurement of runway friction, assessment of precipitant drag potential and position and height of significant snow banks.

1.4 PRECIPITANT DRAG

1.4.1 There is a requirement to report the presence of snow, slush, ice, or water on a runway, as well as to make an assessment of the depth of snow, slush or water. Reports of assessment of contaminant depth on a runway will be interpreted differently by the operator for the take-off as compared with the landing. For take-offs, operators will have to account for the precipitant drag effect, and, if applicable, aquaplaning on take-off distance requirements based on information which has been made available to them. With regard to landings, the principal hazard results from loss of friction due to aquaplaning while the drag effects of the precipitants would assist aircraft deceleration.

1.4.2 However, apart from any adverse effects from precipitant drag which may occur on take-off or loss of braking efficiency on landing, slush and water thrown up by aircraft wheels can also inflict significant damage on airframes and engines and risk flame-outs. This is further reason to exercise the prime requirement to remove precipitant from the runway rather than, for instance, devoting special efforts towards improving the accuracy of measurement and reporting the runway braking action on a contaminated runway.

1.4.3 The *Airworthiness Technical Manual*, Part III, calls for provision in the Aeroplane Flight Manual of information on landing distances to be reasonably expected during a moderate to heavy rain and on runways covered with snow (dry snow, wet snow, compacted snow), slush or ice. In order to ensure that the final distances correspond to conditions representative of an average wet, well-soaked runway, it would be necessary to verify, during the certification tests, the level of friction existing.

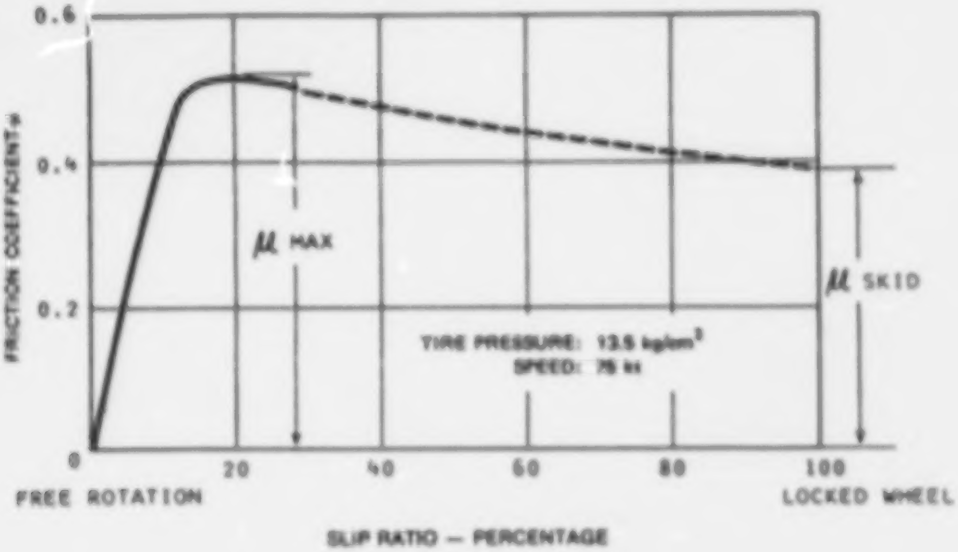


Figure 1-1. Relation between percentage slip and friction coefficient on a wet runway

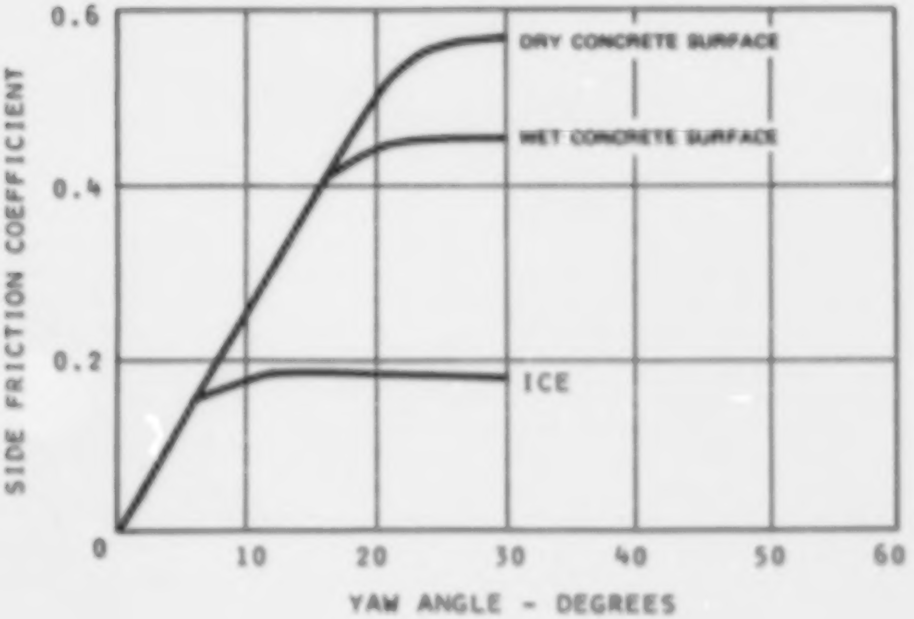


Figure 1-2. Typical variation of side friction coefficient with yaw angle

1.5 EXPLANATION OF TERMS

1.5.1 It is not possible to discuss methods of measuring friction and assessing precipitant depth without first considering some of the basic phenomena which occur both under and around a rolling tire. For the sake of simplicity, these can, however, be given in a qualitative manner.

Percentage slip

1.5.2 With the older type of aircraft brakes, not having an anti-skid system, the harder the pilot applied the brakes the more torque he could develop. In applying the brake pressure he slowed down the wheel and, provided he had sufficient torque, he could lock it. Assuming an aircraft speed of 185 km/h (100 kt) and the speed of the tire at its point of contact with the ground 148 km/h (80 kt) the tire would slip over the ground at a speed of 37 km/h (20 kt). This is termed 20 per cent slip. Similarly, at 100 per cent slip the wheel is locked. The importance of this term lies in the fact that, as the percentage slip varies, so does the amount of friction force produced by the wheel, as shown in diagrammatic form in Figure 1-1 for a wet runway. It will be noted that the maximum friction force occurs at about 15 per cent slip, a fact which modern braking systems make use of to increase braking efficiency. This is achieved by permitting the wheels to slip at approximately this percentage. When measuring the friction characteristics of a wet runway a slip ratio of about 15 per cent should therefore be used. It should be noted, however, that when measuring the braking action of a snow- or ice-covered runway surface a slip ratio of about 10 per cent is considered to be acceptable.

1.5.3 The importance of this curve from the viewpoint of runway friction coefficient measurements is that the value at the peak of the curve (termed μ maximum) can, when plotted against speed, represent a characteristic of the runway surface, its contamination, or the braking test device carrying out the measurement and is, therefore, a standard reproducible value. This type of device can thus be used to measure the runway friction coefficient. On a snow- or ice-covered runway the measured value can be given in a meaningful form to a pilot. On wet runways the measured value can be used as an assessment of the friction characteristics of the runway when wet.

Locked wheel

1.5.4 The term locked wheel is exactly as implied and the friction coefficient μ skid produced in this condition is that at 100 per cent slip in Figure 1-1. It will be noted that this value is less than the μ max attained at the optimum slip. Tests have shown that for an aircraft tire μ skid varies between 40 per cent and 90 per cent of μ max, subject to runway conditions. Even so, vehicles using a locked wheel mode have also been used to measure the runway friction coefficient.

Side friction coefficient

1.5.5 When a rolling wheel is yawed, such as when a vehicle changes direction, the force on the wheel can be resolved in two directions, one in the plane of the wheel and other along its axle. The side friction coefficient is the ratio of the value of the force along the axle divided by the vertical load. If this ratio is plotted against the angle of yaw on different surfaces, a relationship similar to Figure 1-2 is established.

1.5.6 It can be seen that, provided the wheel is yawed at an angle greater than 20 degrees, the side friction coefficient can be used to give a number representing the runway friction coefficient. Allowing for certain other considerations, the wheel can in effect be made to work at μ max.

"Normal" wet friction and aquaplaning

1.5.7 When considering a wet or water-covered runway, there are certain separate but related aspects of the braking problem. Firstly, "normal" wet friction is the condition where, due to the presence of water on a runway, the available friction coefficient is reduced below that available on the runway when it is dry. This is because water cannot be completely squeezed out from between the tire and the runway and, as a result, there is only partial contact with the runway by the tire. There is consequently a marked reduction in the force opposing relative motion of tire and runway because the remainder of the contacts are between tire and water. To obtain a high coefficient of friction on a wet or water-covered runway, it is, therefore, necessary for the intervening water film to be displaced or broken through during the time each element of tire and runway are in contact. As the speed rises, the time of contact is reduced and there is less time for the process to be completed; thus, friction coefficients on wet surfaces tend to fall as the speed is raised, i.e. the conditions in effect become more slippery. Secondly, one of the factors of most concern in these conditions is the aquaplaning phenomenon whereby the tires of the aircraft are to a large extent separated from the runway surface by a thin fluid film. Under these conditions, tire traction drops to almost negligible values and aircraft wheel braking as well as wheel steering for directional control is, therefore, virtually ineffective. A description of the three principle types of aquaplaning known to occur is given below. Further guidance on water depth and its influence on aquaplaning is contained in 2.1.

1.5.8 The typical reduction of friction when a surface is wet and the reduction of friction as aircraft speed increases are explained by the combined effect of viscous and dynamic water pressures to which the tire/surface is subjected. This pressure causes a partial loss of "dry" contact the extent of which tends to increase with speed. There are conditions where the loss is practically total and the friction drops to negligible values. This is identified as viscous, dynamic or reverted rubber aquaplaning. The manner in which these phenomena affect different areas of the tire/surface interface and how they change in size with speed is illustrated in Figure 1-3, which is based on the three zone concept suggested by Gough. In zone 1 where there is aquaplaning and in zone 2 where there is viscous pressure, friction is virtually zero whereas one can assume dry friction in zone 3. As this zone will gradually decrease as speed increases the μ will be reduced at the same proportion as zone 3 is reduced. It can be assumed that the proportion between the zones will be the same if two wheels are running at the same fraction of their aquaplaning speed.

1.5.9 In the case of viscous aquaplaning, loss of traction can occur at relatively low speeds due to the effect of viscosity in preventing water from escaping from under the tire footprint. However, a very smooth runway surface is required and such can be encountered in areas that have become heavily coated with rubber deposited by tires during wheel spin-up at touchdown, or which have been subjected to polishing by traffic. Viscous aquaplaning is associated with damp/wet runways and, once begun, can persist down to very low speeds. Viscous aquaplaning can occur during the braking portion of either an interrupted take-off or landing ground roll.

1.5.10 Dynamic aquaplaning will occur beyond a critical speed which is a function of tire pressure. The condition is a result of an inertial effect of the water in which the downward pressure (inflation pressure) of the tire is insufficient to displace the water from out of the footprint in the short time of contact. Dynamic aquaplaning can occur on a runway with inadequate macrotexture at speeds beyond the critical aquaplaning speed and provided the fluid is deep enough. It is associated with a coverage of fluid of measurable depth on the runway and occurs at a critical velocity which is a direct function of the tire pressure. The higher the tire pressure the higher the velocity at which (dynamic) aquaplaning will occur. However, the trade-off will be that with increasing tire pressures the achievable wet friction will generally decrease in the speed range up to aquaplaning. Dynamic aquaplaning is experienced during the higher speeds of landing and take-off ground roll. As little as 1 mm of standing water has been found to be sufficient to support dynamic aquaplaning. This relatively small depth can occur in heavy rain showers.

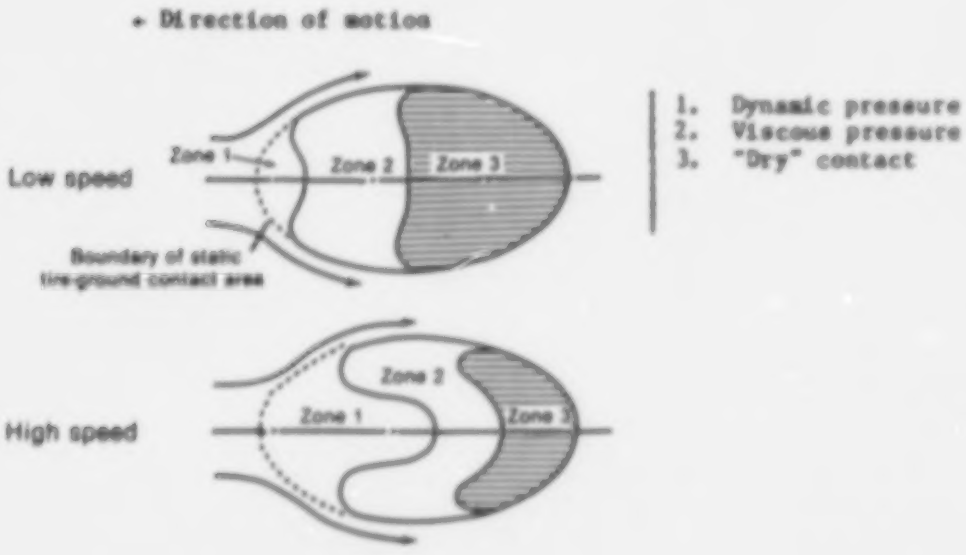


Figure 1-3. Areas of tire/surface interface

1.5.11 There is still much to be learned regarding rubber reversion but present thinking indicates that superheated steam is generated between the tire footprint and the runway surface at a temperature of approximately 200°C which results in melting of the affected area of the tire tread. One theory is that the melted rubber acts as a seal preventing escape of the high pressure steam. Following incidents when rubber reversion is known to have occurred, white marks have been observed on the runway surface characteristic of the "steam cleaning" action. Reverted-rubber aquaplaning can develop in any situation and any speed where a tire is non-rotating (braked or unbraked) for a prolonged period of time. Accordingly, avoidance of wheel lock-up appears to be the important preventative measure in this case.

Coefficient of friction

1.5.12 The classic definition of coefficient of friction is the ratio between the tire friction force and the vertical load acting on a tire.

Braking system efficiency

1.5.13 As already indicated, modern anti-skid braking systems are designed to operate as near to the impending skid value (μ_{max}) as possible, and braking system efficiency (μ_{eff}) is usually taken as the percentage of this value which the brake can achieve. The efficiency tends to increase with speed, tests on an older type of system on a wet surface having given values of 70 per cent at 56 km/h (30 kt) rising to nearly 80 per cent at 222 km/h (120 kt). Even higher values have been claimed for the more modern systems. For anti-skid systems in use on many transport aeroplanes the effective braking coefficient, μ_{eff}, has been empirically established as:

$$\mu_{eff} = 0.2\,\mu_{max} + 5/7\,\mu_{max}^2 \quad \text{for} \quad \mu_{max} \text{ less than } 0.7$$

and

$$\mu_{eff} = 0.7\,\mu_{max} \quad \text{for} \quad \mu_{max} = 0.7 \text{ or greater}$$

Rolling resistance

1.5.14 Rolling resistance is the drag caused by the elastic deformation of the tire and a flexible supporting surface. It is approximately 0.02 times the vertical load on the tire. For the tire to rotate, the coefficient of rolling friction must be less than the friction coefficient between the tire and the runway.

Friction/speed curves

1.5.15 Water is one of the best lubricants for rubber and as stated in 1.5.7 displacement of water and penetration of thin water films in the tire contact area takes time. There are a number of runway surface parameters which affect the drainage capability in the tire contact area. If a runway has an open macrotexture allowing the water to escape without significant build-up of water pressures then the friction coefficient will be less affected by speed. Conversely, a surface of a closed macrotexture will experience a larger drop in friction with increase in speed. Another parameter is the sharpness of the texture (microtexture) which determines basically the friction level of a surface, as illustrated in Figure 1-4.

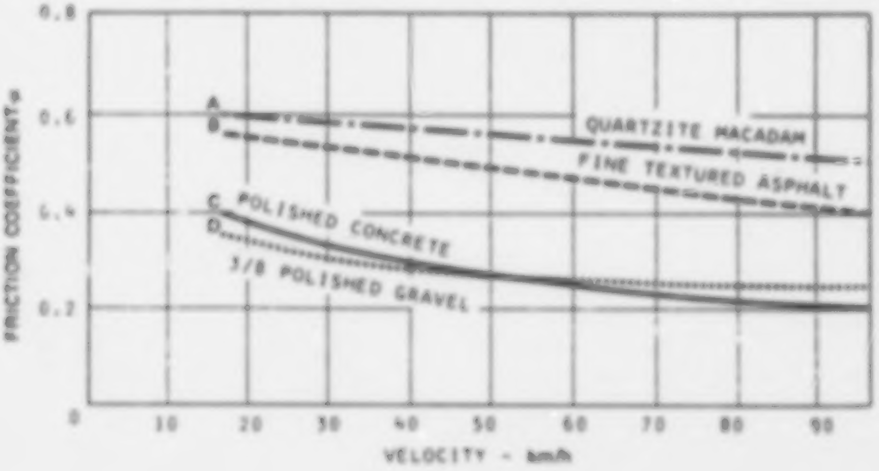


Figure 1-4. Relationship between braking friction coefficient achieved with anti-skid braking on different textured surfaces at certain operating conditions

1.5.16 As speed increases, the friction coefficients of the two open-textured surfaces A and D drop slightly whereas the friction coefficients for surfaces B and C drop more appreciably. This suggests that the slope of the speed/friction curve is primarily affected by the macrotexture provided. The magnitude of the friction coefficient is predominantly affected by the roughness of the asperities, A and B having a sharp microtexture, C and D being smooth. From the friction point of view, therefore, runway surfaces should always provide the combination of sharp and open textures. A friction/speed curve is, therefore, indicative of the effect of speed on the wet surface friction coefficient, particularly if it includes the higher velocities (i.e. approximately 185 km/h (100 kt)) and can be useful to operators for qualitative assessments.

Surface texture

1.5.17 The friction coefficient between the tire and the runway depends on a number of factors such as speed, surface texture, type of runway contamination, depth of contamination, tire rubber compound, tire structure, tire tread pattern, tread surface temperature, tire wear, tire pressure, braking system efficiency, brake torque, wheel slip ratio and season of the year. Some of these factors have effects on each other and their individual effect on the magnitude of the friction coefficient varies in significance. The parameter, however, which determines most significantly the magnitude of achievable wet friction and the speed/friction relationship is runway surface micro/macrotexture.

Chapter 2

Assessment of Basic Factors Affecting Friction

2.1 WATER DEPTH AND ITS INFLUENCE ON DYNAMIC AQUAPLANING

2.1.1 The critical speed at which aquaplaning (see 1.5.7 to 1.5.11) occurs depends on how it is defined, as illustrated in Figure 2-1. If aquaplaning speed is defined as the point at which the fluid drag versus speed curve reaches its maximum, this will not agree with the speed at which the wheel ceases to revolve. The pilot has little interest in the former but he does wish to know when there is insufficient grip between the tire and ground to cause the wheel to spin up, that is to overcome rolling resistance, since he cannot apply effective braking from that point. It is probable that there is still some contact with the ground at this speed but not sufficient to cause the wheel to revolve. When no part of the tire is in contact with the ground, this speed probably approximates more closely the point at which the fluid drag stops increasing (*i.e.* at the peak of the solid line in Figure 2-1).

2.1.2 Dynamic aquaplaning will start at a velocity in kilometres per hour (or in knots) which is approximately equal to 624 times (356 times) the square root of the tire pressure in kPa. The process is not entirely understood. It was encountered unexpectedly during friction trials with an instrumented aircraft when a friction coefficient value of $\mu = 0.05$ was measured with the brakes on. The record of wheel speed showed there was insufficient rolling drag to spin up the wheel each time the automatic brake slowed it down.

2.1.3 Another important point is that, once having aquaplaned, the ground speed must be reduced well below the aquaplaning speed before the wheel will spin up again. This phenomenon is shown clearly in tests with a 23 cm wheel conducted by the University of Bristol as shown in Figure 2-2.

2.1.4 It will be noticed that, at a pressure of 206.8 kPa and a load of 90 kg, the tire aquaplanes at approximately

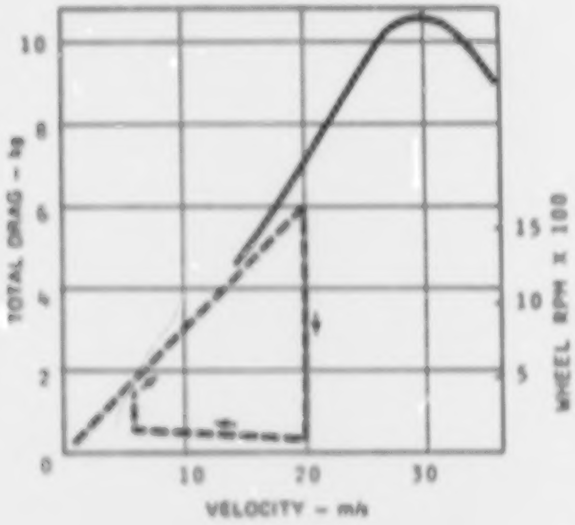


Figure 2-1. Variation of total drag of a small tire with wheel RPM and speed

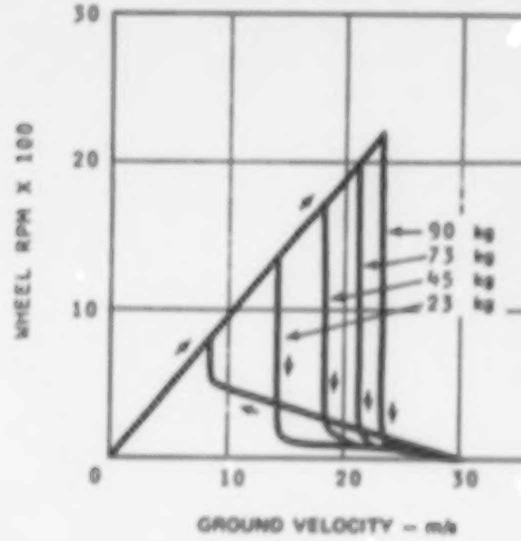


Figure 2-2. Variation of wheel rotation with ground speed and load

23 m/s but does not regain ground speed until the velocity is reduced to 9 m/s. A change in the load on the tire also changes its aquaplaning speed, if this is assumed to be the velocity at which the wheel spins down. The practical aspect demonstrated by this experiment is that an aircraft tire will not regain contact with the ground sufficiently to give any effective braking until a speed well below that required to initiate aquaplaning is reached.

2.1.5 It is clear that dynamic and viscous aquaplaning will only occur if there is a sufficient depth of water on the runway to preclude it being cleared from the tire contact area sufficiently quickly to permit some dry contact. This then becomes a matter of drainage and it mainly a question of runway micro/macrotexture while the tire tread pattern will contribute comparatively little to tire footprint drainage. A suitably grooved tire will provide additional drainage channels which, however, decrease in effectiveness as the grooves wear to their permitted limits. It is now generally accepted that the risk of aquaplaning can be greatly minimized by the provision of an adequate micro/macrotexture of the runway surface. This aspect is dealt with in the *Aerodrome Design Manual*, Part 3 — Pavements.

2.1.6 In order to determine how the water depth required to sustain aquaplaning varies with surface texture, the United Kingdom College of Aeronautics conducted tests for their aquaplaning characteristics on brushed (not wirecombed) concrete and on scored concrete surfaces. By building ponds on each surface in the intended wheel track and with a measuring device set into the runway, it has been possible to determine the height of an aquaplaning tire above the runway. Figure 2-3 was produced by plotting the depth of water above the marker against the height of tire above the runway.

2.1.7 It is seen that, once having aquaplaned (which might occur in a puddle), the tire will not regain contact with the runway in more than 0.6 mm of water if the surface is brushed concrete and the tire pressure 827 kPa. The higher the tire pressure the greater the depth of water required to sustain aquaplaning. Also, the coarser the surface macrotexture, the greater the water depth required. These trials also revealed that aquaplaning can start in milliseconds once the critical water depth is encountered. The provision of good surface drainage and suitable texture are most essential requirements to minimize the risk of aquaplaning and to enhance generally the wet friction characteristics.

2.1.8 Since the initial water depth varies with surface texture, it is vital to translate the information into practical terms. Some method or device must be used to define texture, which, in itself, presents a difficult problem because the size, shape and angularity of the aggregate are all significant. Various methods and measuring techniques are in use. Information on these methods and techniques is contained in 2.3.

2.1.9 It is apparent that few States, if any, are at present providing information on runway water depth,

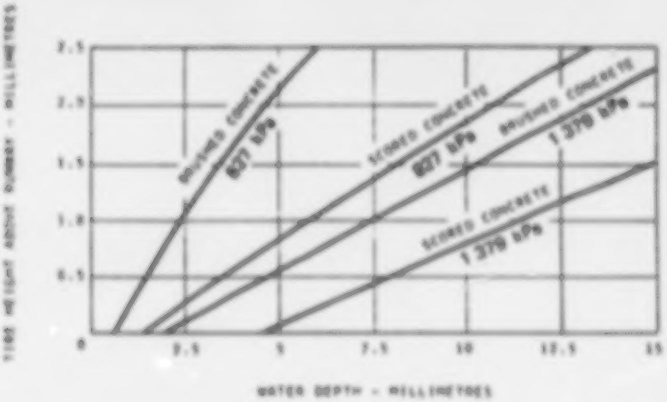


Figure 2-3. Height of a tire above a runway in different water depths, surface textures and tire pressures at above aquaplaning speed

although in some States using preferential runway systems the practice is to change the landing runway under wet conditions to a longer one and/or one having less crosswind.

2.1.10 There has been some speculation on whether measuring water depth could perhaps replace measuring runway friction. To this end, a study was undertaken so as to attempt to ascertain the list of requirements to be met by water depth measuring devices. The study showed that the devices should, *inter alia*, be accurate, easy to use, quick to operate and be capable of measuring the depth of a layer of water to a value of up to 10 mm. Further, the runway occupancy time must be minimal and the readings should not be affected by the concentration of salt on the surface of the water layer. None of the devices known to be used by States appears to meet these requirements, although at least one of them is considered to fulfil the requirements for research work purposes. Although possible, it appears that it would not be practical to develop a device which could meet all the above requirements. The main reason for this is that it appears preferable to develop programmes aimed at improving the surface texture and drainage of runways rather than measuring the water depth. The devices could only be of some significance in rare cases of extremely heavy rain. Even assuming that a device meeting the specified requirements is developed, another big difficulty appears to be the number and location of devices needed for a runway. In the light of the above, it has been concluded that standardization of water depth measuring devices with the object of measuring runway friction is not considered practical.

2.1.11 *Other considerations.* The depth of fluid is, of course, only one consideration. The density and viscosity existing within any given depth is most important. For any given measurable depth, consideration of fluid density, fluid viscosity, runway texture, tire tread design/wear and runway contamination is required before any operational application can be assessed.

2.2 SURFACE CONTAMINANTS

2.2.1 The presence of fluid state contaminants (wet snow, slush or standing water) on runways can have an extreme effect upon the operation of aircraft. Variations in the nature of the contaminant and critical effect of its depth have created difficulties in satisfactorily evaluating the resulting precipitant drag effect. Operational measures for dealing with the problem of take-off from slush or water-covered runways are contained in the *Airworthiness Technical Manual*.

2.2.2 There exists during operation on runways with measurable depths of fluids, in addition to the presence of critically low levels of friction and the adverse effects of aquaplaning, the retardation effects to free rolling referred to as "precipitant drag". More specifically, precipitant drag can be broken down to include: a) fluid displacement drag; b) wheel spin-down characteristics; c) wheel spray patterns and fluid spray (impingement) drag. Based on actual aircraft testing plus ground-run tests, the levels of precipitant drag attained are a direct function of the following variables and their applied combination, namely, square of ground speed, vertical load, tire pressure, fluid density, fluid depth and wheel location.

2.2.3 When an unbraked tire rolls on a fluid covered runway, the moving tire contacts and displaces the stationary runway fluid. The resulting change in momentum of the fluid creates hydrodynamic pressures that react on the tire and the runway surfaces. The horizontal component of the resulting hydrodynamic pressure force is termed "fluid displacement drag" or a retarding force to forward movement. The vertical component of this reaction is termed "fluid displacement lift" or the reacting force introducing potential dynamic aquaplaning and wheel spin-down tendencies. Additional fluid forces reacting to forward movements are "fluid spray drag" and "fluid spray lift" created on the aircraft when some of the displaced runway fluid in the form of spray subsequently impinges on other parts of the aircraft such as the tires, landing gear, high lift/drag devices and rear mounted engines.

2.2.4 Fluid displacement drag is primarily critical for the acceleration characteristics of the aircraft on take-off. The effects of fluid displacement drag are also experienced during deceleration; however, the advantages of the retardation during deceleration are largely offset by the general reduction of the friction coefficient and the possible occurrence of aquaplaning.

2.2.5 As already mentioned, the problem of precipitant drag due to surface contaminants is related to the take-off case. Bearing in mind that precipitant drag increases with the square of speed, a critical speed can be reached at which the precipitant drag is equal to the thrust. If the aircraft is then below lift-off velocity, it will never leave the ground. In addition to speed, the precipitant drag will vary with the depth of the contamination and with its density. Since both, particularly the former, can vary throughout the runway length, the complexity of the problem can be well appreciated. Furthermore, the fact that precipitant drag on an aircraft consists of two primary components, i.e. the displacement of the contamination by the wheels, and the material thrown up by the wheels hitting the aircraft, means that the total precipitant drag will vary with different types of aircraft.

2.2.6 One method to measure the depth of the fluid is to take a large number of readings with a ruler or other device and calculate the average. This would be satisfactory if the depth were relatively uniform but in practice that is rarely the case.

2.2.7 The pilot will know the maximum depth of a specific fluid contaminant in which he is allowed to take off, and will need reports on runway state in terms of each third of the runway, of which the second or last third will have the most significance.

2.3 SURFACE TEXTURE

2.3.1 Surface texture is considered to be the main clue to differences in the braking friction coefficient of a wet runway. Runway surfaces contain both macro and micro textures. Macrotexture is the coarse texture evidenced by the aggregate or artificially applied texture such as grooving. Macrotexture can be measured by a number of methods and is primarily responsible for bulk water drainage from the surface. Microtexture, on the other hand, is the texture of individual pieces of aggregate that can be felt but cannot be directly measured. Microtexture is important in penetrating very thin water films. Thus, macrotexture is primarily used to increase bulk water drainage thereby reducing the tendency for aircraft tires to experience dynamic aquaplaning while microtexture is most important in reducing the onset of viscous aquaplaning that is associated with very thin water films. Since both macro and micro textures have significant effects on wet friction coefficients, it can be stated, *a priori*, that only general trends can be established using only measurements of macrotexture. Such data as are available do show a general trend in favour of large macrotextures to increase wet friction coefficients.

2.3.2 Annex 14 recommends that the average surface macrotexture depth of a new surface should not be less than 1 mm to provide good friction characteristics when the runway is wet. Although a depth of less than 1 mm may still provide good drainage, when constructing a new surface a depth greater than the minimum value must be chosen as normal pavement use will result in surface deterioration. If some surface texture depth additional to the minimum is not provided when constructing a pavement surface, then maintenance action will soon be required.

2.3.3 It is logical, therefore, to apply a technique which will qualify the gradient of the speed/friction curve of a surface by measurement of surface macrotexture. To obtain an average macrotexture depth, representative samples should be taken over the entire surface. The number of samples required will depend upon variations in the surface macrotexture. To this end it is desirable, before surface texture measurements are made, to conduct a visual inspection of the surface to determine significant changes in pavement surfaces.

2.3.4 It is generally recognized that the most suitable techniques available for measuring the surface macrotexture depth are the grease and sand patch methods. A description of these two methods as well as others which can be used for measuring average texture depth is given below.

Sand and Grease Patch Methods

2.3.5 A known volume of grease or of sand particles of known size is spread over the surface until all the cavities are filled. If the known volume is then divided by the area covered, the mean depth of the cavities can be found. Measurements of this type can be expected to indicate only the effect of speed on the speed/friction curve and this has been confirmed by practical experiment (see 1.5.15).

2.3.6 Examples of measurements by the grease and sand patch methods are shown below.

GREASE PATCH METHOD

A. Apparatus required

1. A metal cylinder open at both ends with an internal volume of about 16 000 mm³. The actual volume is not critical, provided it is accurately known. Suitable dimensions might be: internal diameter pipe, 25.4 mm; length 32.3 mm.

2. Putty knife

3. A tight-fitting plunger and rod to expel the grease from the cylinder.

4. A rubber-faced aluminium or wooden squeegee some 30-40 mm in width.

5. Masking tape.

B. Test procedure

1. The test cylinder is first packed with any general purpose grease using the putty knife in such a way as to avoid entrapped air and the ends are squared off using the putty knife. Two parallel lines of masking tape are applied to the runway surface about 10 cm apart and a third line of masking tape is placed at right angles to and at one end of the two parallel lines of tape. The grease is expelled from the cylinder by means of the plunger on to the test area and worked into the voids in the surface to the levels of the peaks of the surfacing and in a rectangular shape between the parallel masking tapes. Care is to be taken that no grease is left on the masking tapes or squeegee.

2. Measure the volume of the test cylinder and the dimensions of the grease patch. The average surface depth of the voids in mm is given by the equation:

$$\text{Surface texture index} = \frac{\text{Volume of grease (mm}^3\text{)}}{\text{Area covered (mm}^2\text{)}}$$

After completion of the grease patch tests, the grease must be removed from the runway surface.

SAND PATCH METHOD

A. Apparatus required

1. A metal cylinder of 86 mm internal depth and 19 mm internal diameter.

2. A flat wooden disc, 64 mm in diameter with a hard rubber disc 1.5 mm thick stuck to one face, the reverse face being provided with a handle.

3. Dry natural sand, with a rounded particle shape, which will pass a 300 micron sieve and be retained on a 150 micron sieve.

B. Procedure

1. Dry the surface to be measured and sweep clean with a soft brush. Fill the cylinder with sand, tapping the base three times on the surface to ensure compaction, and strike off the sand level with the top of the cylinder. Pour the sand into a heap on the surface to be tested. Spread the sand over the surface, working the disc with its face kept flat, in a circular motion so that the sand is spread into a circular patch with the surface depressions filled with sand to the level of the peaks.

2. Measure the diameter of the patch to the nearest 5 mm. The texture depth is 31 000/D^2 where D is the diameter of the patch in mm.

2.3.7 The following methods are also used for measuring surface macrotexture:

a) direct measurement on the pavement. The real length of a line running over this surface is measured;
b) stereophotographic method. By means of a specially constructed stereo camera, a part of this area is photographed. From the resulting contour lines a profile is drafted, the length of which is measured;
c) the bar method. A 0.30 m long row of little thin bars (needles) kept vertical by two holders is placed on the pavement. When the tightening of the clips is diminished, the points of all bars will touch the upper side of the pavement and show a profile line of the surface, the length of which can be measured;
d) the "replica" print. A print of hardening material (plasticine) of the surface is made. After it has been sawn, the length of the replica profile is measured;
e) the carbon print. By means of carbon paper, the copy of the surface of a piece of the pavement is printed on scribbling paper. The length of a profile constructed therefrom is measured;

f) the water-flow measurement. Determination is made of a quantity of water flowing during a certain time from the bottom of a flat cylinder placed on the pavement (loss of height).

2.3.8 By means of such measurements an approximate indication of the surface roughness may be obtained. From volume measurement, the area of the smoothed sand or grease gives such an indication. The quotient of the volume of the smoothed material and its area is called the mean depth of the texture. The quotient of the length of a line measured along the profile of a diagonal section through the pavement and the length of a basis line is called the profile metalling. Inquiries are being made to ascertain whether there is a correlation between the profile ratio and the reduction of roughness but conclusions with regard to this have not yet been made. It is already known that for rough surfaces this ratio is more than 1.05.

2.3.9 It is also important that the mineral aggregate to be used for pavement purposes be laboratory tested for resistance to polishing before being used for the construction of runways. In addition, it should be examined in relation to stiffness against crumbling and splintering of the surface by the action of traffic. The subject of runway surface texture is given detailed consideration in the *Aerodrome Design Manual*, Part 3 — Pavements.

Measurement of surface microtexture

2.3.10 As mentioned earlier, there is no direct measure available as yet to define the required fine scale roughness of the individual aggregates in engineering terms. However, the importance of providing a good microtexture should be emphasized as inadequate microtexture will result in a reduction of friction characteristics of the runway surface. Degradation of microtexture caused by the effect of traffic and weathering may occur within a comparatively short period as compared with that required for degradation of surface macrotexture.

2.4 UNEVENNESS

2.4.1 Although runway constructors go to considerable lengths to produce an even runway with a suitable transverse slope, subsequent consolidation of the runway structure may cause the profile to change and give rise to areas of "ponding". These areas are clearly visible after rain when the drained part of the runway has dried leaving the ponds behind. Remedial action is required when it is found that the ponds are greater than a mean critical aquaplaning onset depth (approximately 3 mm) since aquaplaning, once started, can be sustained on a wet runway by a much smaller depth of water. Further, ponds will, in temperatures below freezing level, form ice patches which can cause considerable difficulties to aircraft operations. Also excessive standing water from the "ponding" could be ingested by aircraft engines resulting in flame-out. Remedial action will normally require resurfacing to effectively alleviate the problem caused by ponding.

Chapter 3

Measuring and Expressing Friction Characteristics On a Wet Runway

3.1 GENERAL

3.1.1 There is an operational need for information on runways which may become slippery when wet. To this end, there is a need to measure periodically the friction characteristics of a runway surface to ensure that they do not fall below an agreed level. Indication of the friction characteristics of a wet runway can be obtained by test devices; however, further experience is required to correlate the results obtained by such devices with aircraft stopping performance due to the many variables involved such as runway temperature, tire inflation pressure, test speed, tire operating mode (locked wheel, braked slip), anti-skid system efficiency, measuring speed and water depth.

3.1.2 The measurement of the surface friction coefficient has been found to provide the best basis for determining braking action. The value of the surface friction coefficient should be the maximum value which occurs when a wheel is braked at a specified percentage of slip but still rolling. Various methods may be used to measure the friction coefficient. Operational considerations will generally determine the most suitable method to be used at a particular airport. As there is an operational need for uniformity in the method of assessing the runway friction characteristics, the measurement should preferably be made with equipment which provides continuous measuring of the maximum friction (15 per cent slip) along the entire runway.

3.1.3 Present technology does not permit a direct and immediate correlation of runway surface friction measurements, taken with a test device, with aircraft stopping performance on wet runways. It has been found, however, that the wet runway friction characteristics of a surface remain relatively constant and deteriorate only slowly over long periods of time, depending on frequency of use. This finding is important, for it eliminates the need to continually measure the friction characteristics of a wet runway. Also, although direct correlation between test devices and aircraft stopping performance does not exist, it is considered that the test devices have the capability to distinguish between runway surfaces which have good or poor friction characteristics. It is, therefore, concluded that instead of reporting on an operational basis the friction characteristics of a wet runway, the runway be periodically tested to ensure that its friction characteristics are of an acceptable standard.

3.1.4 The periodic testing serves two purposes. First, it identifies the sub-standard runways and these locations should be made known to pilots. Second, it provides qualitative information to airport authorities on the condition of the runway surface thus permitting the development of more objective maintenance programmes and justification for development of budgets.

3.1.5 Ideally the distinction between good and poor runway surface friction characteristics when wet should be related to airworthiness criteria for the certification of aircraft. An international agreement for certification of aircraft on wet runways, however, does not exist at this time. Nevertheless, a number of States have operational experience with particular test devices that enable them to initiate programmes for identifying runways which have poor surface friction when wet. This experience can be used to advantage by other States to establish their own programmes and though such programmes may be theoretically imprecise in their relationship to aircraft performance, they are considered adequate to define the good and bad runway surfaces.

3.1.6 The criteria used by a State for evaluating runway surfaces should be published in the State's Aeronautical Information Publication (AIP). When a runway surface is found which does not meet the criteria, a NOTAM should be issued until such time as corrective action has been taken.

3.1.7 Furthermore, it is desirable to publish in the AIP the calibration number of the runway surface friction of a new runway. This value is the average value for the entire runway and should be obtained when the runway is wet but clean. If the surface friction differs significantly along major portions of a runway, i.e. in the order of 100 m, a calibration number should be given for each portion of the runway. It may also be expected that the value(s) will deteriorate with time and therefore the date of the test should be given. This information is considered of value for it gives an over-all indication of the surface friction of a runway, and because the portion of a runway between the touchdown zones is normally not affected by rubber build-up.

3.2 MEASUREMENT

3.2.1 There are four reasons for the requirement to measure the friction value of a wet runway. They are:

a) to provide periodic calibrations of the value of the wet runway surface friction;
b) to assess the slipperiness of runways when wet;
c) to determine the effect on friction when drainage characteristics are poor; and
d) to determine the friction of runways that become slippery under unusual conditions.

3.2.2 Runways of code number 3 or 4 should be calibrated when first constructed or after resurfacing to determine the wet runway surface friction characteristics. Although it is recognized that friction reduces with use, calibration identifies the friction of the relatively long central portion of the runway that is uncontaminated by rubber deposits from aircraft operations and is therefore of operational value. Calibration tests should be made on clean surfaces. If it is not possible to clean a surface before testing, then for purposes of preparing an initial report a test could be made on a portion of clean surface in the central part of the runway. For uniformity and to permit comparison with other runways, the tests should be made with a uniform water depth and, therefore, the use of test equipment with a self-wetting device is necessary.

3.2.3 The calibration number should be obtained by averaging the results of measurements made with the test device. If the friction characteristics differ significantly along major portions of a runway, the calibration number should be obtained for each portion of the runway. A portion of runway in the order of 100 m long may be considered significant for the determination of the calibration number. The calibration number(s) should be made available together with the date of the test and the type of test device used.

3.2.4 Friction tests of existing surface conditions should be taken periodically in order to identify runways with low friction when wet. A State should define what minimum friction it considers acceptable before a runway is classified as slippery when wet and publish this value in the State's Aeronautical Information Publication (AIP). When the friction of a runway is found to be below this reported value, then such information should be promulgated by NOTAM and appropriate action initiated to improve the friction. Friction measurements should be taken at intervals that will ensure identification of runways in need of maintenance or special surface treatment before the condition becomes serious. The time interval between measurements will depend on factors such as aircraft type and frequency of usage, climatic conditions, pavement type, and pavement service and maintenance requirements. As is the case for calibration tests, these tests should be made with a uniform water depth, and the use of test equipment with a self-wetting device is required.

3.2.5 When it is suspected that the friction characteristics of a runway may be reduced because drainage, due to inadequate slopes or depressions, is poor then an additional test should be made but this time under natural conditions representative of a local rain. This test differs from the previous one in that water depths in the poorly cleared areas are normally greater in a local rain condition. The test results are thus more apt to identify problems of aquaplaning than the previous test. If circumstances do not permit tests to be conducted during natural conditions representative of a rain, then this condition may be simulated.

3.2.6 Even when the friction has been found to be above the level set by the State to define a slippery runway it may be known that under unusual conditions the runway may have become slippery. These conditions are known to occur at certain locations when the initial rainfall on a runway, following a prolonged dry spell, results in a very slippery condition which is unrepresentative of the over-all wet friction characteristics of the runway. When such conditions are known to exist then a special test should be made as soon as it is suspected that the runway may have become slippery.

3.2.7 This situation is a temporary one which remedies itself as further rainfall washes the runway's surface. It is believed to be caused by the emulsification of dirt and other deposits which are precipitated onto the runway and which may originate from adjacent industrial complexes. A similar phenomenon has, however, been observed on runways located in desert or sandy areas, and also in humid tropical climates where microscopic fungoid growths are believed to be responsible.

3.2.8 When the results of any of the measurements identified in 3.2.2 through 3.2.6 indicate that only a particular portion of a runway surface is slippery then action to promulgate this information and, if appropriate, take corrective action is equally important.

3.2.9 When conducting friction tests on wet runways, it is important to note that, unlike compacted snow and ice conditions in which there is very limited variation of braking action with speed, a wet runway usually produces a marked drop in friction with an increase in speed. However, as the speed increases the rate at which the friction is reduced becomes less. Among the factors affecting the friction co-efficient between the tire and the runway surface, texture is particularly important. If the runway has an open texture allowing the water to escape either through the tire tread pattern or beneath the tire, then the friction value will be less affected by speed. Conversely, a smooth surface will experience a larger drop in friction with increase in speed. Accordingly, when testing runways to determine their friction and whether maintenance action is necessary to improve it, a speed high enough to reveal these friction/speed variations should be used.

3.2.10 An accurate measurement of the friction characteristics of a wet runway can only be obtained if the relevant factors are measured as accurately as is practicable. Such items as the calibration of the test device, condition of the tires, the amount of water on the surface, etc., have a significant effect on the final friction value for the particular surface. It follows that the most stringent control of the measuring techniques must be exercised.

3.2.11 States should specify a friction level below which it is required to take maintenance action and to report that the runway may be slippery when wet. Experience with different test devices shows the following criteria in use in some States for specifying the friction characteristics of new runway surfaces aqd establishing maintenance levels:

Test device	Design objective for new runway surface	Maintenance level	Test water depth (mm)	Test speed (km/h)
1	2	3	4	5
Mu-meter —				
method 1	0.7	0.5	1.0	65
method 2	0.65	0.45	0.5	130
Skiddometer	0.5	0.35	1.0	130 } with high
and Surface	0.6	0.4	1.0	95 } pressure
Friction Tester	0.7	0.5 1.0		65 } tire
Stradographe	0.6	0.35	1.0	65

The values in columns 2 and 3 are averaged values representative of the runway or significant portions thereof.

3.2.12 In countries where the Skiddometer and Surface Friction Tester are used it is considered desirable to test friction values at more than one speed, and test speeds of 130, 95 and 65 km/h are used. If tests are to be performed at a single speed, a speed of 130 km/h is considered preferable.

3.2.13 The measurements specified in this section may not directly correlate with aircraft performance. However, research work indicates that reasonable correlation between friction measurements and the friction available for aircraft exists provided the measured values are referenced to a common base line.

3.2.14 Because the value of the friction coefficient is so dependent on surface texture, it may vary with the source of the construction material and the method of construction. Also, some areas of a runway are more frequently used than others, or have a rubber deposit, all of which will change the basic friction coefficient value. Thus, it can be concluded that the whole runway length needs to be measured. To cover the required width, measurements should be carried out along two tracks; namely, along a line on each side of the centre line approximately 3 m or that distance from the centre line at which most operations take place.

3.2.15 To minimize variations in the friction measurements caused by the techniques used in applying finish to the surface, runs should be made in both directions and a mean value taken. Significant variations between the readings obtained in both directions should be investigated. Additionally, if a measurement of the friction is made along a track 6 to 7 m from the runway edge it will provide a datum of the unworn and uncontaminated surface for comparison with the centre channel.

3.2.16 A continuous measuring device (e.g. Skiddometer, Surface Friction Tester, or Mu-meter), a diagonal braked vehicle, an LPC trailer or a Stradographe can be used for measuring the friction values for wet runways. A method of measuring or assessing the friction value when no friction test devices are available at the airport is described in Appendix 1.

3.3 REPORTING

3.3.1 There is a requirement to report the presence of water within the central half of the width of a runway. It is also required to make an assessment of water depth where possible. To be able to report with some accuracy on the conditions of the runway the following terms and associated descriptions should be used:

Damp — the surface shows a change of colour due to moisture.

Wet — the surface is soaked but there is no standing water.

Water patches — patches of standing water are visible.

Flooded — extensive standing water is visible.

3.4 INTERPRETATION OF LOW FRICTION CHARACTERISTICS

3.4.1 There is a requirement to make available information that, due to poor friction characteristics, a runway or portion thereof may be slippery when wet. There may be a significant deterioration both in aircraft stopping performance and directional control.

3.4.2 If a landing is to be made, it is advisable to ensure that the landing distance required for slippery conditions, when this is specified in the Aeroplane Flight Manual, does not exceed the landing distance available. When considering the possibility of an aborted take-off account should be taken of the runway friction characteristics on that portion of the runway which will be used for the emergency stop. A safe stop from V_1 (decision speed) may not be possible and depending on the distance available and other limiting conditions the take-off may need to be delayed.

Chapter 4

Measuring and Expressing Braking Conditions On Snow- or Ice-Covered Runways

4.1 GENERAL

4.1.1 There is an operational need for reliable and uniform information on runway braking action on snow- or ice-covered runways. Meaningful indications of braking action in terms of friction coefficients can be obtained by test devices because the friction coefficient is fairly independent of speed for these conditions. Nevertheless, further experience is required to improve correlation of the results obtained by such devices with aircraft stopping performance due to the many variables involved such as aircraft mass, speed, braking system behaviour, tire and undercarriage characteristics.

4.1.2 The measurement of the surface friction coefficient has been found to provide the best basis for determining braking action. The value of surface friction should be specified as the maximum value which a wheel will develop when braked at a fixed percentage of slip, but still rolling. Various methods may be used to measure the friction conditions. Operational consideration will generally determine the most suitable method to be used at a particular airport. As there is an operational need for uniformity in the method of assessing and reporting runway friction, the measurement should preferably be made with equipment which provides continuous measuring of the maximum friction along the entire runway. A chart, based on results of tests conducted on selected snow- or ice-covered surfaces, showing the correlation between certain test devices on snow- or ice-covered surfaces is presented in Figure 5-1. Details concerning the correlation between these vehicles are given in 5.3.

4.2 THE AIRPORT PROBLEM IN CHANGING CONDITIONS

4.2.1 The day-to-day requirement for measuring the runway braking action under winter conditions must be determined by the authority having the responsibility of deciding whether the runway is fit for use. If this is the Air Traffic Service Unit and it is advised by the meteorological service to expect ice or snow, it will probably need hourly reports as a minimum and, certainly, whenever there is reason to believe there has been a significant change in the runway state. If the airport is open on a 24-hour basis, it will need to know the situation throughout this period. If it is closed during the night, then it would need to have a check made before opening for traffic.

4.2.2 There are special circumstances under which particular attention is required, such as when runway temperatures are fluctuating about the freezing point or, for example, under changing weather conditions when a warm moist air flow affects a very cold runway. Under circumstances such as these, it has also been found that friction values can differ significantly depending upon the runway surface material used. Measurements should, therefore, be taken on the actual runway in use and not on an adjacent runway or taxiway which may be constructed of a different material.

4.2.3 The reliability of tests by measuring devices conducted in conditions other than compacted snow or ice is highly questionable. This will apply in particular when there is a thin layer of slush or uncompacted snow on a runway. In such cases, the wheels of the test device may penetrate the layer whereas the wheels of the aircraft will not, particularly at high speed. Thus, aircraft may experience poor braking action and poor directional control at high speed and will only encounter the braking action representative of the friction test at low speeds. The results of friction tests obtained with different test devices in such cases may be at great variance because of differences in test methods and, for a particular method, because of different characteristics of the vehicle and different individual techniques in performing the test. Care is also essential in providing runway friction information to pilots under conditions when water is observed on top of ice.

4.2.4 The effectiveness of providing runway friction information will depend upon the degree of correlation which can be achieved with the actual stopping performance of aircraft. This information is undoubtedly required to assist operators in making operational judgements, but in the case of ice-covered runways, the measuring and reporting of friction coefficients should only be regarded as an interim procedure while clearing and other remedial measures to restore the runway to full serviceability are being completed. Although the coefficient of friction for a wet surface decreases with an increase in speed, tests on ice or compacted snow do not indicate an appreciable difference in friction coefficient values between the comparatively low speeds used when testing and aircraft speeds.

4.2.5 In considering the relative merits of measuring the friction coefficient on a snow- or ice-covered runway, compared with effective measures to maintain a surface free of any contaminants at all times, it should be noted that immediate removal of snow and ice should receive high priority. Nevertheless, there are circumstances which justify a requirement for friction measurement and, therefore, the development of acceptable methods. For example, incidents have occurred involving loss of braking action or directional control on runways which were apparently clean and dry. Such deterioration in the friction coefficient, while not visually apparent, could have been revealed by measurement. Incidents of this kind can occur at an airport having few or no traffic movements at night, when flight operations are resumed in the early morning and frost is observed, or when under freezing conditions the runway surface temperature falls below the dew point (e.g. through radiation).

4.2.6 When a runway is icy, the friction value is liable to change. Under these circumstances, frequent measurements of runway friction coefficient are essential and call for co-operation and development of suitable procedures between the appropriate air traffic service units and the crew operating the friction measurement vehicle.

4.2.7 At an airport which regularly experiences heavy snowstorms, it is sometimes necessary to discontinue snow removal operations for a short period in order to permit flight operations to continue. Under these circumstances, it is unlikely that the runway will be completely clean and measurements will be required as vital information to aircraft. Moreover, despite measures to keep the runway clear, slippery patches may remain. Measurements are, therefore, necessary to detect those areas requiring further treatment and to provide information to pilots on the overall braking action along the runway.

4.2.8 The use of a test device giving continuous measurement information is to be preferred. However, for day-to-day operations when dealing with a snow- or ice-covered runway, it is essential that the vehicle used be capable of providing the required information quickly and in an operationally meaningful form.

4.2.9 The practicality of measuring the depth of dry snow, wet snow or slush on a runway has been questioned since it is a time-consuming process which could be more usefully employed in clearing the precipitants from the pavement, particularly since the removal of slush is a relatively fast and simple operation. Moreover, procedures for measuring the depth of precipitants are generally based on the assumption that there is a uniform layer on the runway and this is seldom found in practice.

4.3 ACCURACY REQUIRED OF INFORMATION REGARDING BRAKING ACTION

4.3.1 For a modern turbo-jet transport aircraft, the difference in stopping distance on a dry runway, as compared with an ice-covered runway, can amount in extreme cases of poor braking action to an extra distance in the order of 900 m. There is as yet no general agreement that accurate prediction of the variation in stopping distances due to low μ conditions is possible. Further research is required to correlate the measured braking coefficient to the braking performance of aircraft.

4.3.2 As described in 5.3 an acceptable correlation between aircraft stopping performance and braking test devices is obtained on snow- or ice-covered runways. Aircraft operators, as a result of practical operational experience, have already been able to achieve a practical correlation to a workable degree for certain devices. For this reason, operators have a long-standing requirement for airport authorities to provide runway friction measurement information using one of the devices recognized for this purpose. There is evidence that the more slippery the runway, the more operational reliance can be placed upon the friction measurements currently provided and this tends to endorse the operational requirement. Accordingly, the most useful practical step that can be taken at this stage is to standardize the results of field measurements in wintry conditions and allow operators, through experience, to apply this information to their particular aircraft and operations.

4.4 MEASUREMENT

4.4.1 Braking action should be measured if a runway is covered wholly or partly by snow, ice or frost and repeated as conditions change. Braking action measurements and/or assessments on surfaces other than runways should be made when an unsatisfactory braking action can be expected on such surfaces.

4.4.2 A continuous measuring device (e.g. Skiddometer, Surface Friction Tester or Mu-meter), or a diagonal braked vehicle, can be used for measuring the friction values for compacted snow- or ice-covered runways. A decelerometer (e.g. Tapley Meter or James Brake Decelerometer) may be used on certain surface conditions, e.g. compacted snow, ice and very thin layers of dry snow. Other measuring devices (e.g. LPC trailer or a Stradographe) can be used on snow- or ice-covered surfaces provided they have been correlated with at least one of the types mentioned above. Test devices having high pressure tires may be used in loose dry snow with satisfactory results. A decelerometer or a diagonal braked vehicle should not be used in deep loose snow or slush as each can give misleading friction values. Other vehicles can also give misleading friction values in these conditions unless otherwise proven. Methods of measuring or assessing braking action when no friction measuring devices are available at the airport are described in Appendix 1.

4.5 REPORTING

4.5.1 There is a requirement to report the presence of snow, slush or ice on a runway or a taxiway. To be able to report with some accuracy the kind of precipitants, it is necessary that a uniform method for describing them be used and in this connexion the following definitions for snow and slush on the ground have been incorporated in Annex 14.

Snow (on the ground)

a) *Dry snow.* Snow which can be blown if loose or, if compacted by hand, will fall apart again upon release; specific gravity: up to but not including 0.35.

b) *Wet snow.* Snow which, if compacted by hand, will stick together and tend to or form a snowball; specific gravity: 0.35 up to but not including 0.5.

c) *Compacted snow.* Snow which has been compressed into a solid mass that resists further compression and will hold together or break up into chunks if picked up; specific gravity: 0.5 and over.

Slush. Water-saturated snow which with a heel-and-toe slap-down motion against the ground will be displaced with a splatter; specific gravity: 0.5 up to 0.8.

Note.— Combinations of ice, snow and/or standing water may, especially when rain, sleet or snow is falling, produce substances with specific gravities in excess of 0.8. These substances, due to their high water/ice content, will have a transparent rather than a cloudy appearance and, at the higher specific gravities, will be readily distinguishable from slush.

4.5.2 There is also a requirement to report the braking action of a snow- or ice-covered runway. The braking conditions of a runway should be expressed as "braking action information" in terms of the measured/calculated friction coefficient μ.

4.5.3 Specific numerical μ values are necessarily related to the design and construction of each test device, as well as to the surface being measured and to some extent the speed employed.

4.5.4 It has been found necessary to provide braking action information for each third of a runway. The thirds are called A, B and C. For the purpose of reporting information to aeronautical service units, section A is always the section associated with the lower runway designation number. When giving landing information to a pilot before landing, the sections are, however, referred to as first, second or third part of the runway. The first part always means the first third of the runway as seen in the direction of landing.

4.5.5 Braking action tests are made along two lines parallel to the runway, i.e. along a line on each side of the centre line approximately 3 m or that distance from the centre line at which most operations take place. The object of the tests is to determine the mean friction value for sections A, B and C. In cases where a continuous measuring device is used, the mean values are obtained from the friction values recorded for each section. Corresponding mean friction values obtained by a braked vehicle should be calculated on the basis of at least nine braking tests along each of the two test lines over the usable length of the runway. The distance between each test point should be approximately 10 per cent of the usable length of the runway. If it is decided that a single test line on one side of the runway centre line gives adequate coverage of the runway then it follows that each third of the runway should have three tests carried out on it. Test results and calculated mean friction values can be entered in a form similar to that shown in Figure 5-9. Where applicable, figures for stopway friction value should also be made available on request.

4.5.6 When reporting the presence of dry snow, wet snow or slush on a runway, an assessment of the mean depth over each third of a runway should be made to an accuracy of approximately 2 cm for dry snow, 1 cm for wet snow and 0.3 cm for slush.

Chapter 5

Runway Friction Test Devices

5.1 POSSIBILITY FOR STANDARDIZATION

5.1.1 Up to the present time a number of different types of test devices for measuring runway friction/braking action incorporating diverse functioning principles and differing in their basic technical characteristics have been created and put into service in various States (see Table 5-1 and 5.5 to 5.12). As a consequence, the result of measurements obtained with them cannot easily be compared. As explained in 5.3 below, the results of the ICAO programme for correlating equipment for the measurement of runway braking action and subsequent tests have shown that an acceptable correlation between the braking action obtained from test devices and between these devices and aircraft stopping performance cannot be obtained on wet surfaces. On snow- and ice-covered surfaces, the correlation between the test devices, although not adequate, is substantially better than on wet surfaces. It is uncertain to what extent a more acceptable correlation will be obtained with new test devices. In view of the above it is thought that for the time being it is impractical to draft Standards and Recommended Practices concerning the characteristics of the equipment.

5.2 CRITERIA FOR NEW TEST DEVICES

5.2.1 The Eighth Air Navigation Conference (1974) recommended that ICAO develop criteria concerning the basic technical and operational characteristics of equipment for measuring runway friction/braking action. In response to this recommendation, some relevant criteria were developed and transmitted to States. It was thought that the material would assist those States that might be planning to develop new equipment. States, however, were informed of the uncertainty of obtaining a more acceptable correlation between test devices and aircraft stopping performance with any new measuring equipment developed in accordance with the proposed criteria. These criteria, which were reviewed and updated in 1983, are summarized below:

Basic technical characteristics of the test devices

1. *Mode of measurement.* Continuous measurement in motion along the part of the pavement to be tested.
2. *Measured and recorded parameter.* Maximum coefficient of longitudinal tire friction equal to the ratio of the maximum longitudinal friction force to vertical wheel loading.
3. *Travel speed of test device.* Highest practically possible. Minimum speeds on wet runways: 65 km/h; on snow- or ice-covered surfaces: 40 km/h.
4. *Tire of measuring wheel.* Type, size, load and tire pressure — related to the vehicle design. Tread — smooth tire for a wet surface; tread pattern or grooved tread for a snow- or ice-covered surface.
5. *Mode of braking.* During measurement operations; continuous braking with a continuous slip ratio of 15 ± 2 per cent, or about 10 per cent when the device is intended for use on snow- or ice-covered surfaces exclusively.
6. The design of the equipment should exclude any possibility of sustained vertical vibrations of the cushioned and uncushioned mass occurring in all travel speed ranges during the measuring operations, particularly in respect of the measuring wheel.
7. The equipment should possess positive directional stability during all phases of operation, including high-speed turns which are sometimes necessary to clear a runway.
8. Calibration of indicator and recording devices. The range of the friction coefficient should be from 0 to 1.0.
9. Presentation of the results of measurements. Should preferably be in recorded form with an indication of the date and time of the measurement (see Figure 5-9).
10. Relative error of measuring equipment in actual operating conditions. Not to exceed 5 per cent.
11. The design of the test device should be such as to ensure its normal operation at any time and in all weather conditions.
12. The technical maintenance of the test device should be such as to ensure the safe execution of the work both during measurement operations and during transportation.

EQUIPMENT	TYPE	NUMBER OF FRICTION MEASURING WHEELS	EQUIPMENT FOR RECORDING DISTANCE	MEASURING WHEEL TIRE PROPERTIES						OPERATIONAL MODE OF FRICTION EQUIPMENT						
				TYPE	SIZE	LOAD ON TIRE kg	PRESSURE kPa	TREAD SMOOTH	TREAD PATTERN	MEASURING WHEEL ANGLE	ANGLE OF TILT AND CAMBER	PERCENTAGE SLIP	CONTINUOUS MEASUREMENT	SPOT MEASUREMENT	SPEED FRICTION MEASUREMENT TAKEN km/h NORMAL	OTHER
SKIDDOMETER TRAILER BV-11	2-wheel trailer towed by auto	1		Radial tubeless	4.00-8	100	117		T 49	0°		15	✓		Constant 65	10 to 96
MU-METER TRAILER	3-wheel trailer tow bars	2	Rear wheel drives the recorder mechanism — input drives digital distance counter	Tube	4.00-8 16 × 4	78	69 ± 3	✓		15° included angle — toed out condition	2.1° +0.25°	13.5	✓		Constant 65 ± 5	up to 160
JAMES BRAKE DECELERO-METER (JBD)	Damped pendulum														40	
TAPLEY METER	Damped pendulum														40	
DIAGONAL BRAKE VEHICLE (DVB)	Automobile with 2 wheels diagonally braked	2	5th wheel at rear of automobile	Radial bias tubeless	G78-15	600	165 ± 3	✓		0°		100		✓	Deceleration from 96 km/h to full stop	up to 130
STRADOGRAPHE	Automobile with a 5th wheel	1	Measurement on 4 wheels	Radial tube	135 × 380 mm	150	150			0°		Variable, normally 15%			100	up to 130
LPC TRAILER	1 wheel trailer towed by auto	1	Speed is measured directly on gear box	Radial tube	165 × 380 mm	250	180			0°		100%			60	up to 140
SURFACE FRICTION TESTER (SFT)	Automobile with 5th wheel in trunk	1		Radial tubeless	4.00-8	140	200 700		Synthetic rubber Natural	0°		10 — 12	✓		Constant 96	up to 130
MILES TRAILER	Single wheel trailer tow bars	1		Radial tube	16 × 4	340	120		✓	0°		100		✓	Deceleration from 100 km/h to full stop	up to 150

Table 5-1. Characteristics of test devices (see 5.5 to 5.12)

EQUIPMENT	MEASUREMENT OF FRICTION						WET FRICTION SURVEYS				TEMPERATURE RANGE FOR CONDUCTING FRICTION SURVEYS	ASTM SPEC. DESIGN.	NUMBER OF OPERATORS TO CONDUCT FRICTION SURVEYS
	FRICTION VALUE MEASURED	DISTANCE OVER WHICH FRICTION VALUE AVERAGED	TYPE OF GRAPHIC RECORD PRODUCED	EVALUATION OF PAVEMENT SURFACE CONDITION (μ or BN)			METHOD OF WATER APPLICATION	SIMULATED WATER DEPTH FOR WET FRICTION VALUES	WATER TANK CAPACITY (L)	WATER FLOW RATE (L/m)			
				GOOD	MEDIUM	POOR							
SKIDDOMETER TRAILER (BV-11)	Coefficient of friction μ 0.0 to 1.0	Runway divided into three equal sections, μ calculated using average for the three sections	Integrator unit provides paper tape of continuous friction curve for length of runway tested	≥ 0.60	0.40 to 0.59	≤ 0.40	No self water system, use water truck with spray bar or test during rain	Variable, due to variations on pavement surface			-40°C to 40°C		1
MU-METER TRAILER	Side force coefficient of friction μ 0.0 to 1.0	Same procedure as above, or μ averaged over 150 to 300 m segments	Continuous tape or recorder of Mu-meter — tape or integrator unit	≥ 0.50	0.40 to 0.49	≤ 0.40	Self water system, water applied through nozzles in front of measuring tires	Approximate water depth of 0.5 mm Approximate water depth of 1 mm	1 100	[illegible] at front of each measuring wheel	4°C to 38°C	E 670	1
JAMES BRAKE DECELERO-METER (JBD)	Measures deceleration in ft/sec²	Auto wheels locked and value recorded. Instrument reset to zero and test continued until finished					No self water system, use water truck with spray bar or test during rain	Variable, due to variations on pavement surface					1
TAPLEY METER	Same as above	Same as above					Same as above	Same as above					1
DIAGONAL BRAKED VEHICLE (DBV)	μ-skid calculated from deceleration rate	Vehicle is braked at 96 km/h until stopped. Distance braked recorded	Recorder provides tape for traces of vehicle speed, stopping distance and deceleration with respect to time	≥ 0.52	0.42 to 0.51	≤ 0.41	No self water system, use water truck with spray bar or test during rain	Variable, due to variations on pavement surface	18 900 or more	0.5 L/m² application — usually 2 applications required to approximate 1 mm water depth	-7°C to 40°C	E 524 E 501	2
ODOLIOGRAPH	Coefficient of friction μ 0.0 to 1.0	20 m	Record of continuous friction and [illegible]	≥ 0.60	0.33 to 0.60	≤ 0.33	Self water system	Up to 1.5 mm	100	240	-7°C to 40°C		1
LPC TRAILER	Coefficient of friction μ 0.0 to 1.0	20 m	Usually one measurement every 200 m, graphical or numerical	≥ 0.32	0.23 to 0.31	≤ 0.23	Self water system	1 mm	250	10 L for each measurement	≥ 1°C		2 (1 operator and 1 driver)
SURFACE FRICTION TESTER (SFT)	Coefficient of friction μ 0.0 to 1.0	Same procedure as for Skiddometer, or μ averaged over 100 m segment	Same as for skiddometer	≥ 0.60	0.40 to 0.59	≤ 0.40	Self water system, water applied through nozzle in front of measuring tire	Approximate water depth of 1 mm	600		-7°C to 40°C		1
[illegible] TRAILER	Locked wheel braking force coefficient	Vehicle is braked at 100 km/h until stopped. Distance braked recorded					No self water system, use water truck with spray bar or test during rain	Variable, due to variations on pavement surface					1

Table 5-1. Characteristics of test devices (see 5.5 to 5.12) (cont.)

13. When intended to be used on wet surfaces, test devices should be provided with self-wetting features to enable measurements of the friction characteristics of the surface to be made at a specified water depth ranging between 0.5 and 1 mm.

5.3 CORRELATION BETWEEN FRICTION TEST DEVICES

5.3.1 The possibility of obtaining a useful degree of correlation between friction test devices has been the subject of trials and discussions for some time. As a result of a recommendation made by the Sixth European-Mediterranean Regional Air Navigation Meeting (1971), ICAO arranged a programme for the correlation of equipment used to measure runway friction/braking action. The object of the programme was to define the degree of correlation that existed between various types of test devices used in the measurement of runway friction/braking action. The following types of test devices were included in the programme:

Diagonal braked vehicle (DBV)
James Brake Decelerometer
LPC trailer
Mu-meter
Skiddometer
Stradographe
Tapley Meter

5.3.2 A variety of airport pavement types were chosen and tests were conducted in France and the United Kingdom for the wet surfaces and in Sweden for the snow- or ice-covered surfaces. As a result, a chart showing the correlation between certain friction test devices for compacted snow- or ice-covered surfaces is presented in Figure 5-1 and described in 5.3.5 and 5.3.6. The chart for snow- or ice-covered surfaces did not include correlation with the Stradographe or LPC trailer as tests with these vehicles were not conducted under these surface conditions. Also owing to unfavourable winter conditions prevailing during the tests, it was not possible to conduct any tests on slush conditions.

5.3.3 It was inferred from the tests that it would be possible to extend the application of the correlation charts to other types of test devices not evaluated in the ICAO programme tests, provided that the relationship of such new or modified types of test devices was established with respect to at least one of the types tested in the ICAO programme. It is to be noted that although the object of the correlation programme was achieved, the degree of correlation was such that the chart did not appear to be adequate for operational use.

5.3.4 Further tests have shown that the readings of the friction measuring equipment do not correlate with each other on all wet surfaces. This is because each vehicle measures something different. All have different tires, some are attempting to measure skid, some measure at a constant slip ratio, some measure side force, some measure at a constant speed and some even a speed range, and so on. The correlation of friction measuring equipment on snow- or ice-covered surfaces, although not adequate, is substantially better than on wet surfaces. This is probably because snow and ice conditions have fewer interacting variables, and most important braking action on snow- or ice-covered surfaces is practically not speed dependent. Further work on correlation of equipment on snow- and ice-covered surfaces would be useful and beneficial.

5.3.5 In order to achieve the correlation shown in Figure 5-1 between the above types of test devices, the following practice for tests should be employed:

A. *Continuous measuring device* (e.g. Mu-meter, Surface Friction Tester, or Skiddometer):
   Test speeds: 65 km/h except under icy conditions when, if necessary a lower speed may be used.
   Skiddometer or Surface Friction Tester with high pressure tire, 95 km/h over as large a portion of the runway as test personnel safety permits.

B. *Decelerometer* (e.g. Tapley Meter or James Brake Decelerometer):
   1) Vehicle specifications:
      a) mass: in the order of 1 to 2 tonnes;
      b) tires: winter tires without studs set at the manufacturer's recommended pressures and in a condition not worse than part worn;
      c) brakes: 4 and properly adjusted to ensure a balanced action;
      d) minimum pitching tendency, and with satisfactory directional stability under braking.
   2) The decelerometer should be so set in the vehicle so that it is not bodily displaced by any movement of the vehicle. The instrument used should be set up in the vehicle according to the manufacturer's instructions. Similarly, the device(s) should be maintained and calibrated, according to the manufacturer's recommendations.
   3) Speed at start of measuring: approximately 40 km/h.
   4) Techniques:
      a) brakes should be applied sufficiently hard to lock all four wheels and then released immediately. The time for locking the wheels should preferably not exceed one second;
      b) the decelerometer used should record or retain the maximum retardation occurring during the test;
      c) random very high or very low figures may be ignored when calculating the average values.

C. *Diagonal braked vehicle:*

1) Speed at start of measuring: approximately 95 km/h.
2) Techniques: with the transmission in the neutral position, the diagonal braked wheels are locked until the vehicle comes to a complete stop. Tests are conducted for both dry and snow- or ice-covered surface conditions, and a "wet-to-dry" stopping distance ratio is computed.

5.3.6 The main disadvantage of decelerometers and the diagonal braked vehicle is that since they require the test vehicle to be accelerated to given test speeds, which takes a finite distance, the intervals at which the test readings can be taken are necessarily greater than continuous reading systems. It can be considered, therefore, that these devices are, effectively, spot reading devices.

5.3.7 Where the packed snow or ice conditions are consistent along the runway length, a limited number of tests will be sufficient to confirm the runway state. Where the conditions are variable, tests should be carried out at maximum intervals of 100 m and any significantly high readings discarded before averaging the readings for thirds of the runway.

5.3.8 An example on how the chart in Figure 5-1 is intended to be applied is illustrated below:

A reading of 0.44 (point A) with a diagonal braked vehicle is equivalent to a reading of:

12 with a James Brake Decelerometer (point B)

0.43 with a Skiddometer or Surface Friction Tester (point C)

0.40 with a Mu-meter (point D)

0.36 with a Tapley Meter (point E).

5.4 CORRELATION WITH AIRCRAFT STOPPING PERFORMANCE

5.4.1 In order to be operationally meaningful, it is necessary to determine the correlation between the data produced by the test devices and the actual stopping performance of different aircraft types. At present, there is general agreement that little success has been achieved in this respect.

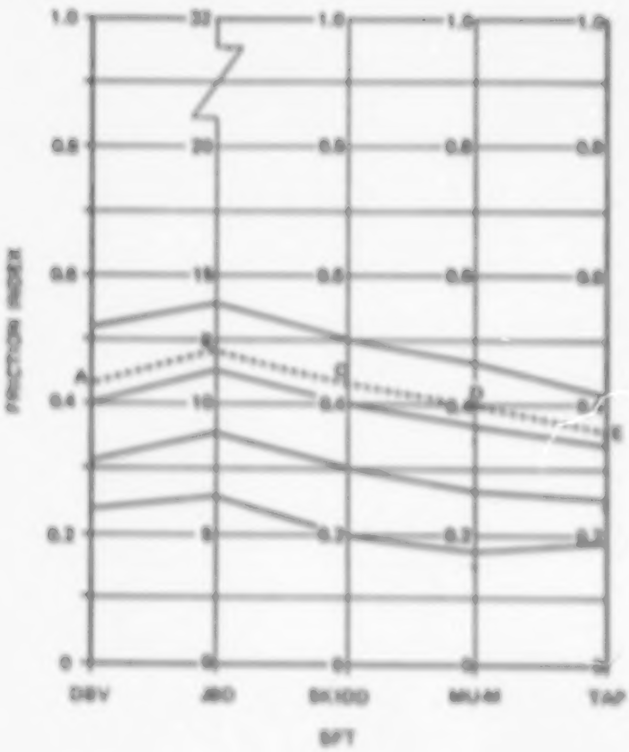
5.4.2 At the time the programme mentioned in 5.3 was arranged, the importance of correlating friction test devices with aircraft stopping performance was recognized but due to the increased complexity and cost involved, the scope of the programme was limited to the friction test devices. Upon the completion of that programme, ICAO established a Secretariat Study Group to co-ordinate States' programmes for testing devices under different conditions and correlation of these devices with aircraft stopping performance. As mentioned in 5.3.4 above, the results of these studies showed that the readings of friction test devices on wet surfaces do not correlate with each other. The results also indicated that due to the numerous interacting variables involved there is also no direct and simple correlation between the readings of these devices and aircraft stopping performance on wet surfaces.

5.5 SKIDDOMETER

5.5.1 This equipment is intended for use in wintry or wet conditions. The principle involved is well known and the practical application for friction measurement is now widely accepted as it permits friction tests to be made with a continuously rotating wheel over long sections of runway under wet or snow-covered pavement conditions without excessive damage to the tread of the tire.

5.5.2 The latest friction test vehicle, BV-11 (Figure 5-2) is towed by an ordinary car, and consists of a frame supported by two independently sprung wheels, tire size 4.00-8/6. A test wheel, tire size 4.00-8/6, is placed between the supporting wheels. The three wheels are connected by means of roller chains and sprocket wheels with a gear ratio chosen to force the centre wheel to rotate with a motion relative to the surface, i.e. the centre wheel is braked with a controlled slip of about 17 per cent when the trailer is towed.

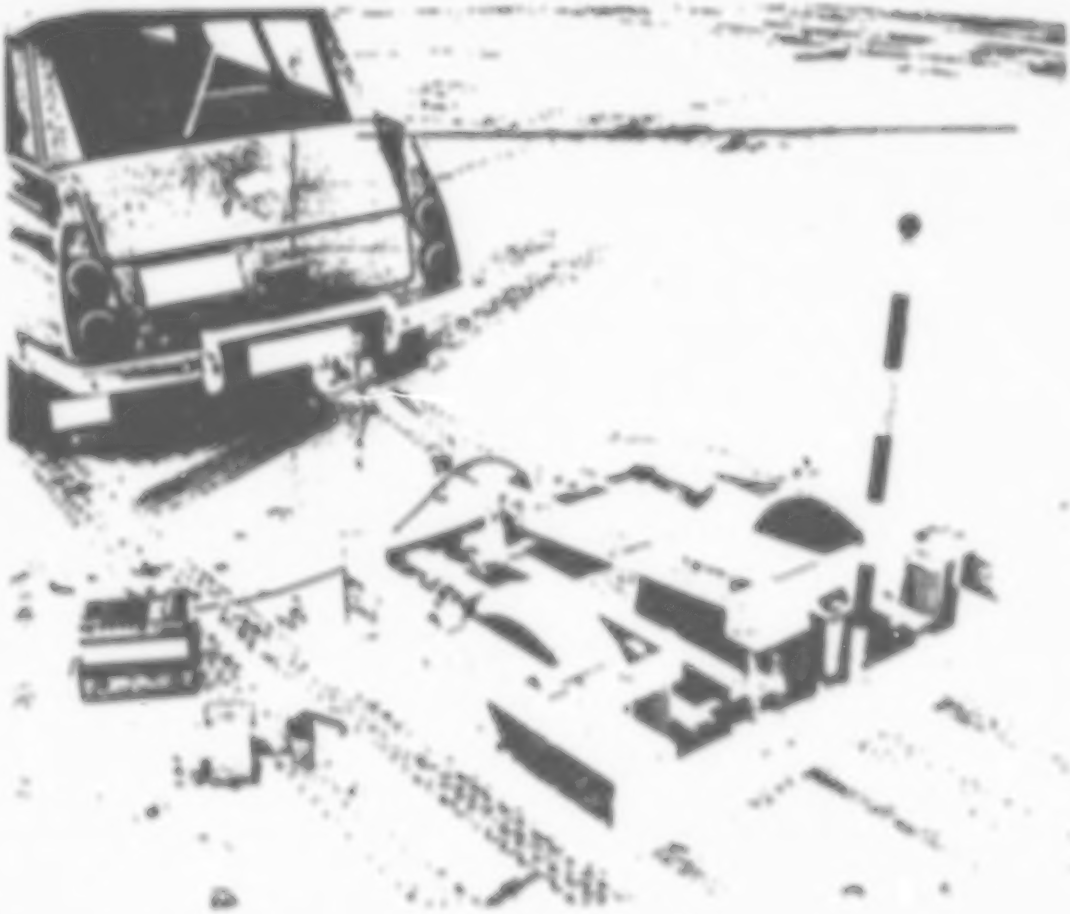
5.5.3 Torque is transmitted from the test wheel to the supporting wheels. The test wheel is forced to operate at a positive slip and thus develops a braking force while the other wheels operate a negative slip (spin) and thus develop a driving force. Since the friction forces on the test wheel and on the supporting wheels act in opposite directions, the towing vehicle is required only to supply the difference between these forces, thus reducing the force required to tow the test vehicle at a certain speed. With the tire continuously rotating at small percentage slip, its entire circumference passes through the contact area in a short time, thus reducing the heat flux to each element. Furthermore, there is little sliding of the tread on the surface, and hence little wear so that continuous operation in a braked condition is possible. The results of a study based on extensive tests have indicated that routine measurements on all types of surface, from ice to dry concrete, can be carried out with fairly good accuracy at the same percentage slip, provided that the same type of



DBV values are shown as the reciprocal of the wet-to-dry stopping distance ratio.

DBV:	Diagonal braked vehicle
JBD:	James Brake Decelerometer
MU-M:	Mu-meter
SKIDD:	Skiddometer
SFT:	Surface Friction Tester
TAP:	Tapley Meter

Figure 5-1. Friction test device correlation chart for compacted snow- or ice-covered surfaces



test tire and the same inflation pressure are used. If another size or type of test tire is to be used it is necessary to check the percentage slip at which the coefficient of friction reaches a maximum. For exploring a runway surface a certain test procedure has been established. If required, the present equipment can be used at speeds up to 130 km/h.

5.6 MU-METER

5.6.1 The Mu-meter is a compact and comparatively lightweight trailer unit which measures, records and presents immediate information on runway surface friction conditions. This data can be relayed via Air Traffic Control without further processing, to pilots prior to take-off and landing. The Mu-meter which is designed for one-man, all-weather operation, can be towed by most vehicles fitted with a suitable hook attachment. It presents friction data in simple digital form on a remote display unit inside the towing vehicle. This data consists of average friction values based on samples taken every 3 m of distance travelled. Earlier Mu-meter models take samples every 6 m.

5.6.2 The Mu-meter is basically a three-wheeled trailer comprised of two friction measuring wheels and a rear wheel (Figure 5-3). The 245 kg trailer is towed by a vehicle at 65 km/h when operational friction measurements are taken. For runway friction "surveys" or "calibration" exercises various methods call for different speeds (e.g. United Kingdom method 130 km/h, United States method 65 km/h). The friction measuring wheels have smooth tires to ensure tread wear has no effect on the results. The rear wheel has a patterned tread tire which provides stability for the trailer during friction surveys.

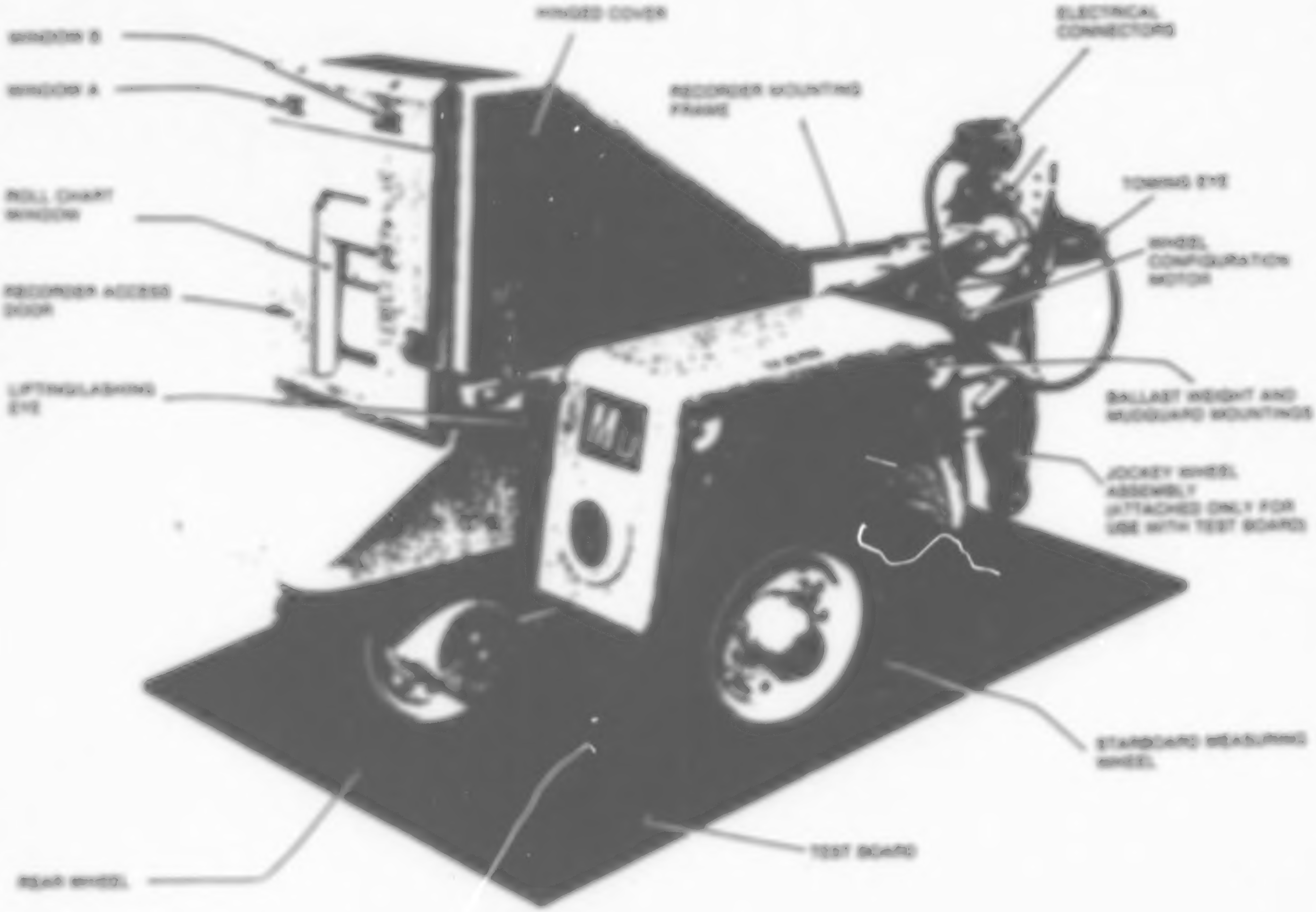

WINDOW B
WINDOW A
HINGED COVER
ELECTRICAL CONNECTORS
RECORDER MOUNTING FRAME
TOWING EYE
ROLL CHART WINDOW
WHEEL CONFIGURATION MOTOR
RECORDER ACCESS DOOR
LIFTING/LASHING EYE
BALLAST WEIGHT AND MUDGUARD MOUNTINGS
Mu
JOCKEY WHEEL ASSEMBLY (ATTACHED ONLY FOR USE WITH TEST BOARD)
STARBOARD MEASURING WHEEL
TEST BOARD
REAR WHEEL

Figure 5-3. Mu-meter with calibration test equipment

5.6.3 The rear wheel also drives the recorder chart drum. The recording apparatus consists of a digital recorder integrator which sums the friction over the distance travelled and a distance counter which counts the distance travelled in units of 6 m. From these indicated totals it is possible to set the two figures on a hand calculator and read the average friction off directly for the distance travelled (Figure 5-4). A chart trace located in the recorder unit provides a continuous permanent record of the friction on the runway. An automatic printout unit which provides friction data for both visual observation and record is located in the cab of the tow vehicle. This unit is synchronized with the recorder unit in the trailer. On early units the distance between automatic friction computation can be preset to anything between 152 m and 777 m. On later models (Mk 3 APO) this can be extended from 152 m to 3 048 m to cover the required facility of dividing long runways into segments of one-third and achieving automatic computation for each segment. This distance on Mk 3 APOs can be readily selected by thumb-wheel switches on the panel face. Test results and calculated average friction values may be entered in a form similar to that shown in Figure 5-9.

5.6.4 To minimize tire wear, the Mu-meter is towed to the threshold of the measuring site in the non-operational configuration i.e. with the side wheels parallel and rear wheel raised. Just prior to approaching the site to be measured, a "POWER ON" and "WHEELS DOWN" selection is made in the towing vehicle whilst in motion, and a motorized screwjack on the trailer sets the side wheels to the preset toed-out position and lowers the rear wheel. Configuration for friction measuring is complete in a few seconds, and relevant basic data such as runway number, time and date is keyed for print-out reference into the cab remote unit.

5.6.5 During friction measuring the toed-out side wheels tend to move apart and are restrained by the load cell generating internal pressure. Fluctuations in this pressure (resulting from varying friction between the measuring wheels and the runway) are recorded on the paper trace and simultaneously relayed to the remote reader/printer.

5.6.6 Any particular hazards observed, such as oil patches or rubber deposits, can be marked on the paper trace at the point of observation, by pressing the reader/printer "EVENT" button.

5.6.7 In order to minimize runway occupancy time the Mu-meter may be operated using a suitable towing vehicle at speeds in excess of 160 km/h, but more normally in the 65-130 km/h range. Tests carried out with the Mu-meter and aircraft have indicated that, with the tire pressure specified the Mu-meter can warn of aquaplaning conditions without the towing vehicle being in hazard.

5.6.8 The Mu-meter can be fitted with a self-watering system for runway calibration or survey work, which obtains readings on runways where the water is metered to a nominal preset water depth enabling acceptable standards to be established, and comparisons between runways, or segments of runways to be made on a common condition datum basis. To discern the presence of aquaplaning when conducting friction surveys on wet runway pavements, the tire pressure for the friction measuring wheels should be set at 69 kPa; then, when the Mu-meter is towed at 65 km/h, this speed is equivalent to 1.2 times the aquaplaning speed and the Mu-meter will indicate an aquaplaning risk.

5.6.9 The equipment is subject to a continuing programme of design improvements to meet the latest user requirements, and these when developed are available in kit form to enable users to update their devices.

5.6.10 In order to speed up transmission of friction data and to enable simultaneous receipt at various terminals, it is expected that an automatic telemetering radio link system will shortly be available for use with the Mu-meter. This will also enable integration of Mu-meter data with that obtained from systems based on permanently sensing heads set at various points on the runway.

5.6.11 When calibrating the runway using the self-watering device or any other wetting method, the Mu-meter can be towed at speeds up to 130 km/h.

5.7 JAMES BRAKE DECELEROMETER

5.7.1 The James Brake Decelerometer (JBD) is a small, light (1.3 kg), relatively inexpensive device used for the reporting of runway surface conditions. It consists of an air damped pendulum coupled to a pointer which indicates deceleration. The pointer remains in position until released by the manual reset button. The instrument is graduated in increments from 0 to 10 m/s^2 the top number being equivalent to the theoretical maximum decelerating capability of the carrier vehicle on a dry surface. These numbers are referred to as the James Brake Index (JBI).

5.7.2 The JBD can be used in any mechanically sound car or light truck fitted with non-studded tires. The JBD is placed on the floor of the vehicle and levelled. It has a low centre of gravity and ordinarily will remain in position when the brakes are applied. The vehicle is driven at a

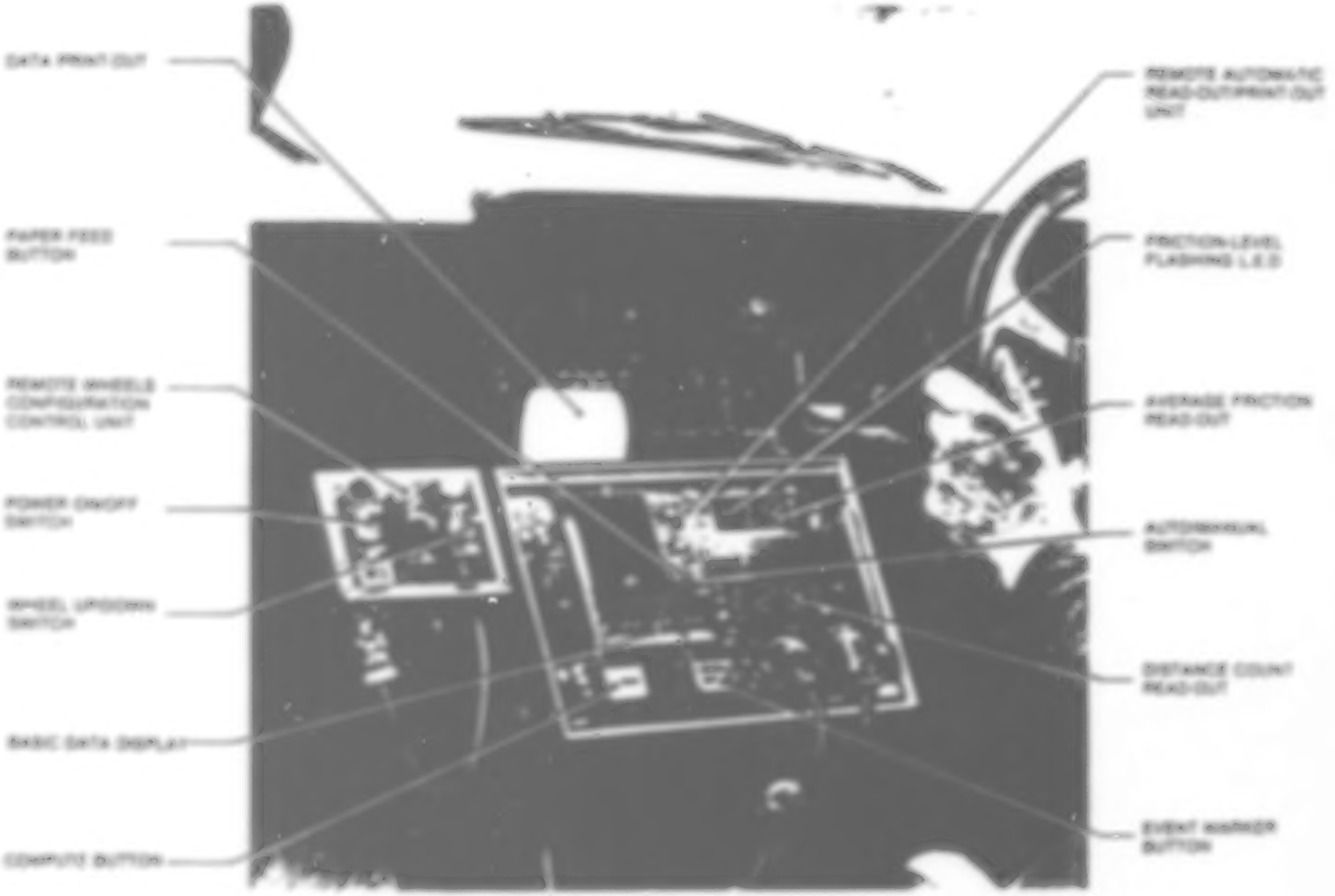

DATA PRINT OUT
PAPER FEED BUTTON
REMOTE WHEELS CONFIGURATION CONTROL UNIT
POWER ON/OFF SWITCH
WHEEL UP/DOWN SWITCH
BASIC DATA DISPLAY
COMPUTE BUTTON
REMOTE AUTOMATIC READ-OUT/PRINT OUT UNIT
FRICTION-LEVEL FLASHING L.E.D
AVERAGE FRICTION READ-OUT
AUTO/MANUAL SWITCH
DISTANCE COUNT READ-OUT
EVENT MARKER BUTTON

Figure 5-4. Automatic print-out unit for Mu-meter

speed of 48 ± 8 km/h and the brakes applied firmly until all four wheels are locked. The reading is taken and the meter reset.

5.7.3 Measurements are made at 300 m intervals at a distance of 9 m on each side of the runway centre line over the entire runway length. The runway is divided into three sections and the JBI recorded for each section is averaged to the nearest whole number. Readings are taken at a frequency appropriate to site conditions and are generally considered valid only when taken on certain surface conditions, e.g. compacted snow, ice or very thin layers of dry snow.

5.8 TAPLEY METER

5.8.1 The Tapley Meter (TAP) is a small, robust, inexpensive, pendulum-based decelerometer readily available world-wide. It consists of a dynamically calibrated oil-damped pendulum in a sealed housing. The pendulum is magnetically linked to a light-weight gear mechanism to which is attached a circumferential scale giving readings in percentage of "g" (and in some instances distance to stop in feet from 32 km/h). A light-weight ratchet retains the maximum scale deflection reached. The mechanism is enclosed in an aluminium case and the scale is read through a window in the top face, the whole assembly being mounted in a cast base plate by means of a fork assembly. Each meter is statically tested and dynamically calibrated before being issued with a calibration certificate.

5.8.2 The Tapley Meter is used in line with the method described in 5.5.5. When setting the Tapley for use, it should be ensured that the Tapley Meter is securely attached to its base plate. To this end, the meter and base plate should be placed on a rigid, basically horizontal surface in the test vehicle where it will be secure during testing, i.e. passenger footwell, etc. There should be no small stones, etc., under the base as it would cause the meter to roll forward under braking. After setting the test lever and meter head to the appropriate positions, the vehicle is accelerated to desired test speeds and tests are carried out in line with procedures in 5.5.5. It is necessary to take a certain number of readings to obtain a reasonable but broad appraisal of the runway condition.

5.8.3 The meter should be checked regularly for signs of oil leaks which would affect the accuracy of the meter. The meter should be recertified every two years and at least at intervals of not more than five years.

5.9 DIAGONAL BRAKED VEHICLE

5.9.1 Diagonal braked vehicles (DBV) are modified commercial automobiles. One such vehicle is a 1980 station wagon equipped with a high-performance engine for fast acceleration, power steering, power brakes and two fifth wheels to provide redundant speed and stopping distance information (Figure 5-5). The braking system was modified to permit one pair of diagonally opposite wheels to be braked while permitting the other diagonal pair to remain unbraked. The braking system has an electrically operated solenoid shut-off valve installed in the brake system of each wheel. The proper valves are actuated by the test personnel to change from the normal four-wheel braking mode for highway use to the diagonal braking mode for conducting tests. This diagonal braking technique enables the DBV to perform locked-wheel skids at high speeds on very slippery surfaces and maintain good directional control while being braked to a complete stop. The braked wheels of the test vehicle are equipped with ASTM tires, conforming to American Society Testing Material Specification E-249, size 7.50 × 14, smooth tread configuration, inflated to 165.5 kPa pressure. The unbraked wheels are equipped with production tires having good tread design to ensure directional control. The use of bald or smooth tread tires on the braking wheels of the DBV eliminates effects caused by tread wear and tread design. Power steering and power brakes assist in maintaining better directional control and in providing necessary brake pressure to lock the two diagonal test wheels. Restraining belts and a roll bar have been installed as safety features. The vehicle is also equipped with a two-way radio and two flashing amber roof lights to meet airport requirements.

5.9.2 Stopping distance of the test vehicle is measured by electronic digital readout meters which are actuated by the brake application switch. The meters record the stopping distance in feet from brake application to vehicle stop. Digital displays of fifth wheel speed in 1.6 km/h increments provide the DBV operator with an accurate indication of vehicle speed (Figure 5-6). An electronic hold circuit in the speed meter system locks the speed on the meter upon brake application. The speed is recorded after the vehicle comes to a complete stop. The speed and distance meters are located on the instrument panel (Figure 5-6).

5.9.3 During a test run, the vehicle is accelerated to a speed of 95 km/h whereupon the driver shifts the transmission to the neutral position. The diagonal braked wheels are locked at the desired test section where the vehicle is braked to a stop. In evaluating pavement surface friction, DBV tests are conducted for both dry and wet surface conditions and a wet/dry stopping distance ratio is

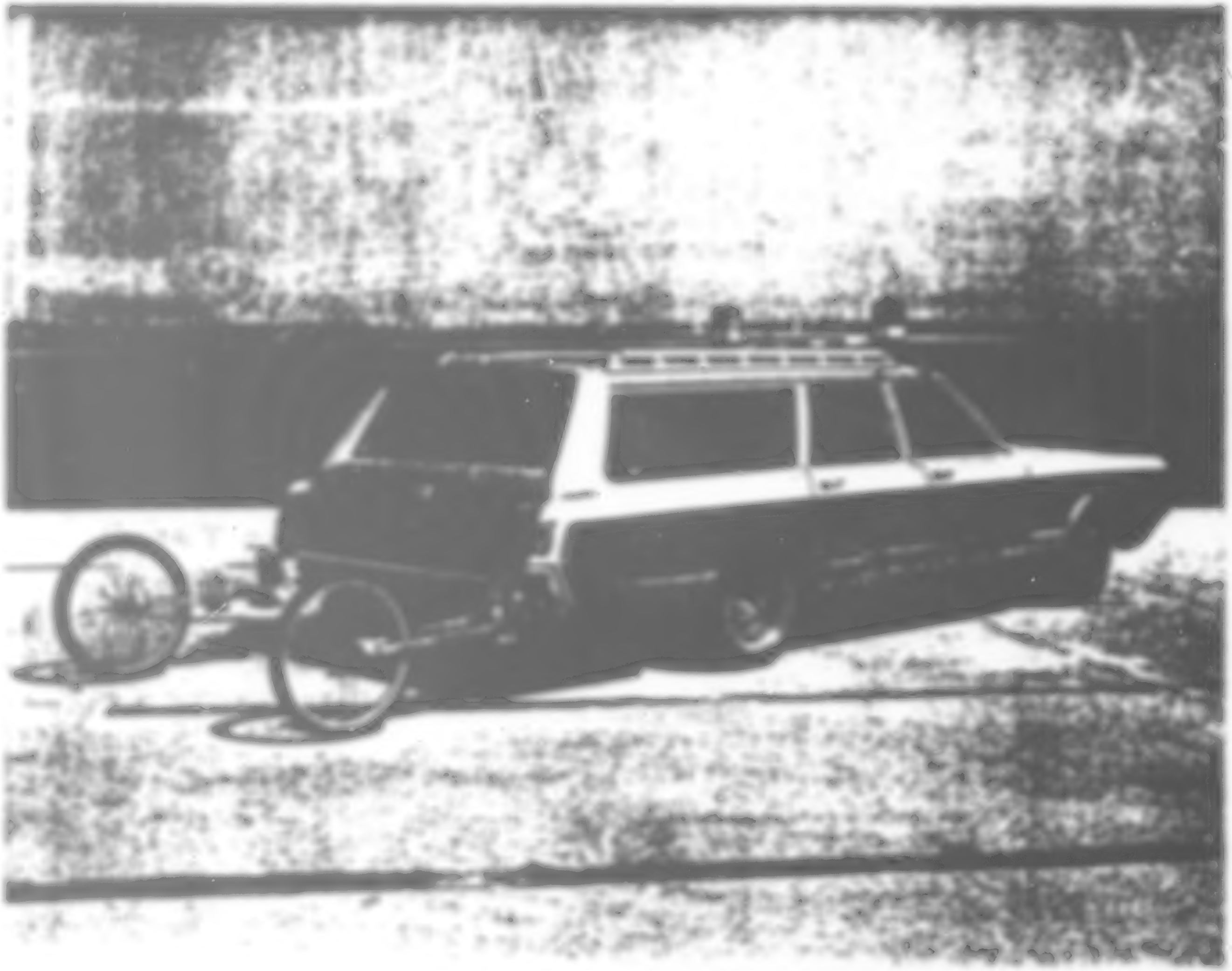


Figure 5.5. Diagonal braked vehicle (DBV)

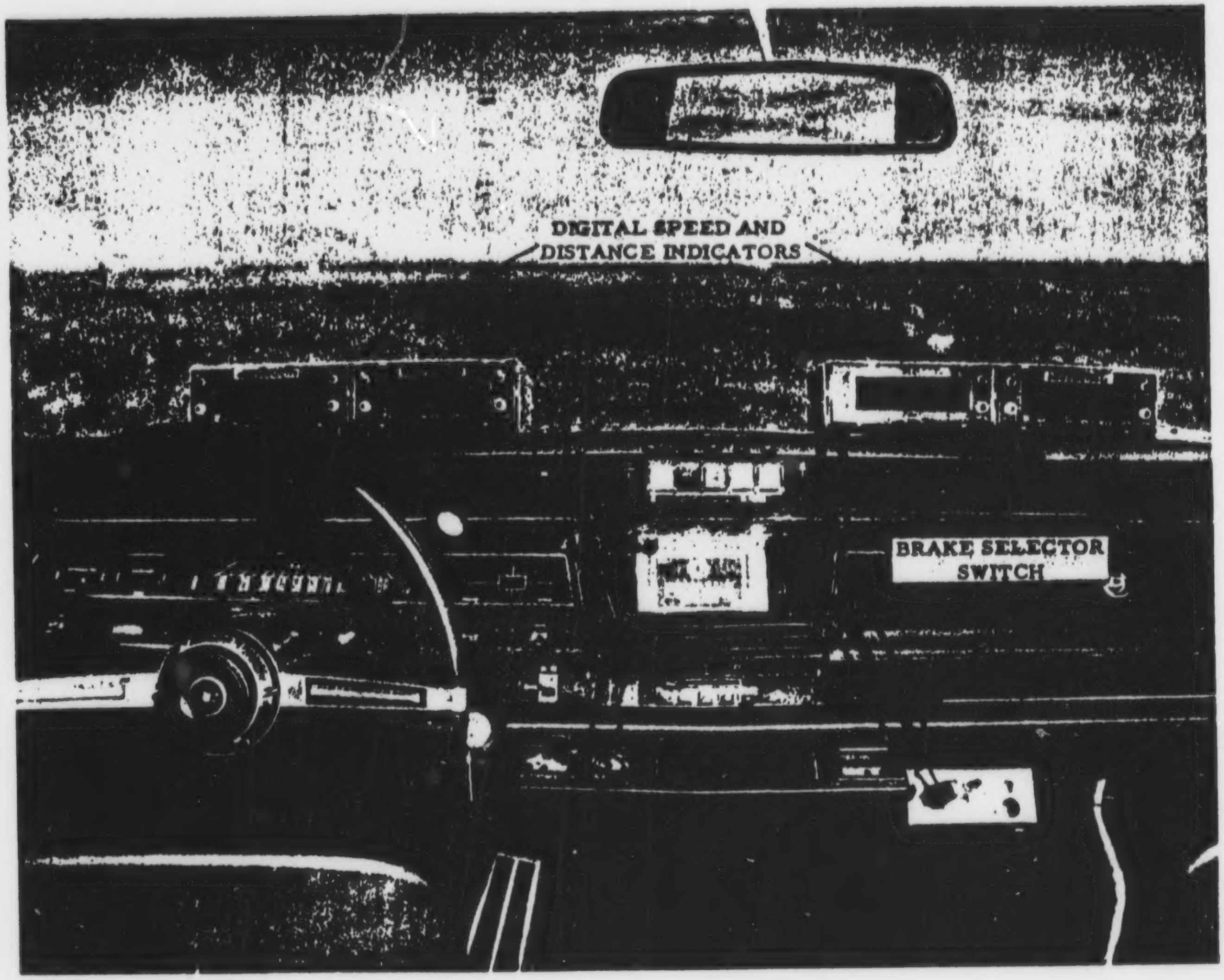

DIGITAL SPEED AND
DISTANCE INDICATORS
BRAKE SELECTOR
SWITCH

Figure 5-6. DBV instrument panel

computed which reflects the pavement's slipperiness for the wet surface.

5.10 STRADOGRAPHE

5.10.1 The measuring device is located on a vehicle (station wagon) which contains a wheel on the longitudinal axis. This wheel can be braked or may even be completely locked. The vertical load applied to the measuring wheel can be set at 100 to 200 kg. The equipment includes a sprinkler and a 350 L water tank. The tire is a smooth radial, 165 mm wide by 380 mm in diameter, inflated to 150 kPa.

5.10.2 The Stradographe is equipped with an electronic chain, which records every second four parameters simultaneously:

- — longitudinal effort;
- — speed of rotation of the wheel;
- — speed of vehicle (usually 100 km/h);
- — vertical load.

5.10.3 All the operations can be programmed in advance and are conducted automatically from a control panel in front of the operator. The longitudinal friction coefficient (LFC), i.e. the ratio of reaction effort to the actual load can be determined with the wheel completely locked or with a given skid rate (between 10 and 20 per cent).

5.11 LPC TRAILER

5.11.1 The equipment consists of a single wheel trailer and a traction vehicle. The trailer has the following components:

- — an automobile wheel equipped with a tire (165 mm × 380 mm) linked to a traction vehicle by an articulated frame on a universal joint and placed under load by two oleopneumatic devices bearing an upper weight frame;
- — a servo-brake enabling the wheel to be immobilized by the action of two brake shoes and controlling a brake for the universal joint, designed to ensure that the trailer does not yaw;
- — a draw bar with a potentiometric dynamometer (0-750 daN) measuring the torque transmitted by the countershaft fixed to the axle;
- — magnetic sensor group to indicate the wheel rotation speed.

5.11.2 An autonomous sprinkler is situated at the rear of the traction vehicle, and the control panel and the recorder are in front.

5.11.3 The LPC trailer enables the longitudinal friction coefficient (LFC) of pavements to be measured, with the wheels locked at speeds between 40 and 140 km/h. At each test, the measuring chain enables three parameters to be recorded:

- — the dynamometric signal giving the LFC;
- — the impulses of the magnetic sensor showing the wheel speed and thus enabling the locking of the wheel to be checked;
- — the wheel locking impulses.

5.11.4 All the measuring operations can be performed automatically. In most cases smooth tires are used.

5.12 SURFACE FRICTION TESTER (SFT)

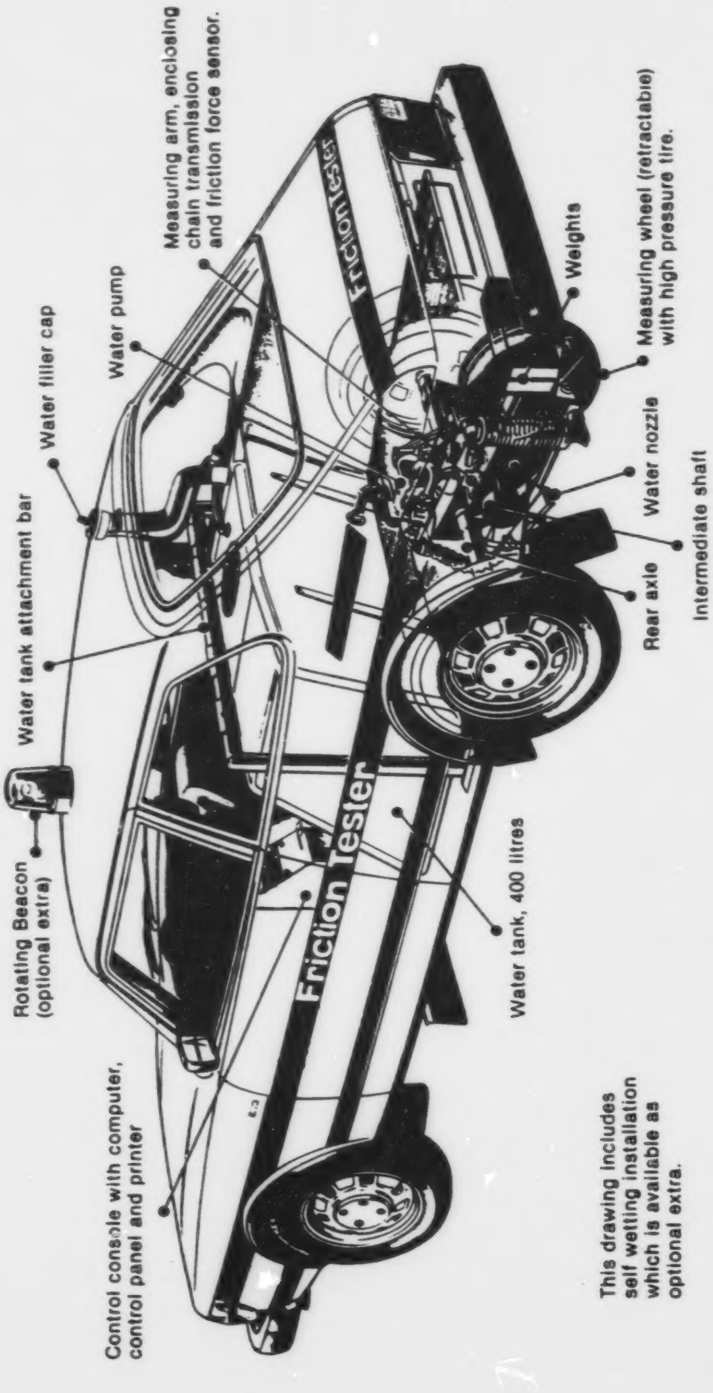
5.12.1 The SFT is a friction test device built into an automobile. It uses a fifth wheel with a constant slip. The design is shown in Figure 5-7.

5.12.2 The fifth wheel is lowered from its retracted position under the luggage compartment of the car when measuring. The measuring wheel, with the measuring tire normally used, has a slip ratio of 10 per cent. The forces acting on the measuring wheel as a result of the friction are measured and the information processed in a minicomputer located in a centre console below the dashboard in the car. Friction values are shown on dashboard friction number gauge as well as being recorded on a paper strip. Figure 5-8 shows the control console in the SFT.

5.12.3 The mini-computer also controls the measuring process according to a preselected programme. This permits the operator to concentrate on driving the friction tester, and enables him to measure the largest possible part of the runway length. During the test run the computer will keep track of friction coefficient, speed, distance covered, distance remaining to be measured, date and time, and will automatically retract the measuring wheel at the end of the test run.

5.12.4 Two programmes have been developed, the standard programme and the runway calibration programme. The standard programme is the programme used in all Surface Friction Testers.

5.12.5 The standard programme has four modes:


Control console with computer, control panel and printer
Rotating Beacon (optional extra)
Water tank attachment bar
Water filler cap
Water pump
Measuring arm, enclosing chain transmission and friction force sensor.
Friction Tester
FrictionTester
Water tank, 400 litres
Rear axle
Intermediate shaft
Water nozzle
Weights
Measuring wheel (retractable) with high pressure tire.

This drawing includes self wetting installation which is available as optional extra.

Figure 5-7. Surface Friction Tester

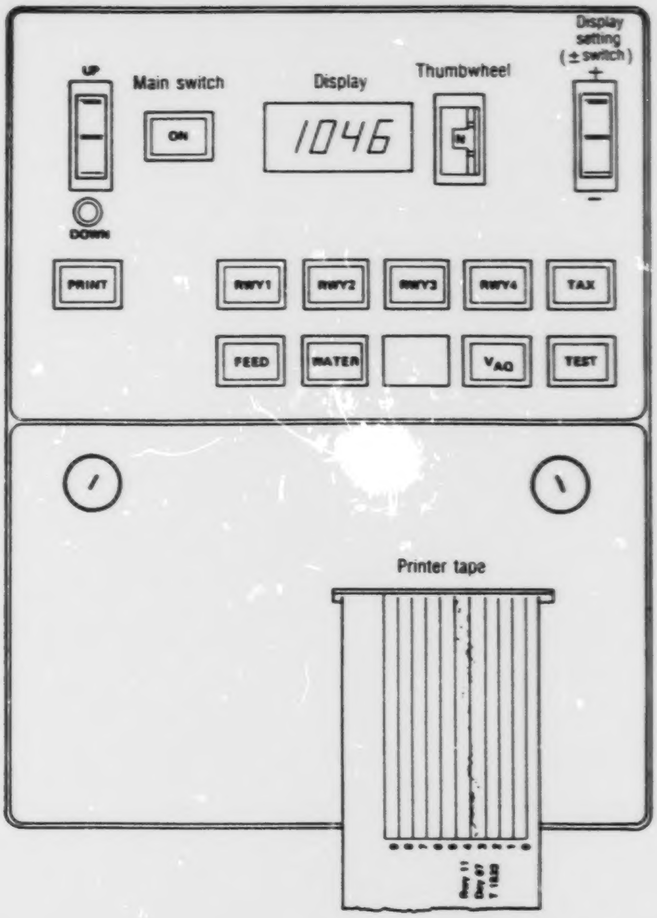


Figure 5-8. Diagram of Surface Friction Tester control console

A Runway mode, when runway number and runway length are programmed into the system, which presents a graph of the friction coefficient, as well as averages for every third of the runway and data for identification of the graph. Speed is also shown on the graph.

B Taxiway mode, presenting a graph of friction coefficient and average friction number for every 300 m.

C Aquaplaning mode, indicating aquaplaning speed for the measuring wheel. The computer samples the speed every time a present friction value is sensed. As standard, the friction value is preset to 0.25.

D Test mode when the computer checks the electronic system and the friction force sensor.

5.12.6 A special programme for runway calibration purposes is available. This programme presents speed and friction coefficient in diagram form, as well as average friction over preselected intervals. To change to the runway calibration programme some plug-in circuit boards are exchanged.

5.12.7 The runway calibration circuit boards and programme incorporate the following features:

Complete preprogramming facilities of runway number and length and taxiway selection

Presentation of a graph
— date and time
— diagram with plot of friction coefficient and speed
— average friction coefficients printed at preselected intervals
— printouts of speed and intervals.

Type of equipment	Time	Location	Programme No.
Date of test	Wind	Direction	
Weather	Condition prior to test		
Runway			
Surface description			

Surface texture tests	Grease (mm)	Water (seconds)
Position 1 Position 2 Position 3		

Tire wear test Left Right	Rubber loss (grams)
Total	

Tests conducted by	Towing vehicle (if applicable)
Method of wetting	Depth of water (mm)
Length covered by trace	Test speeds
Starting at	Ending at
Distance of run from centre line	

Friction results

Speed km/h	32	65	95	130	145	160
1st third Middle third 3rd third						

Recorder chart reference number and means of identification of individual run and speed:

Speed km/h	32	65	95	130	145	160
Section of runway 45 m from centre line giving lowest coefficient of friction (excluding paint markings)						

Note.— The original recorder chart or a print of it must be attached to this form.

Figure 5.9. Mu-meter Test Report Form

Selectable intervals are: 50 100, 150 and 200 m
— selection of intervals and speed presentation is done by switches.

An event marker that allows any number of events to be indicated on the printout. To make it possible to distinguish between different types of observations, four different symbols can be entered at the appropriate spot, by pressing a key on a small, hand-held keypad, connected to the computer.

A data logging output where a cassette recorder can be directly connected to log all data produced by the computer. A separate replay interface box allows direct interface to a larger computer system. The data logging output can also be interfaced to a telemetry radio link.

Test mode where the computer tests the electronics and the friction force sensor.

Preparation for future programme and peripheral device expansion.

5.12.8 A self-watering system is available as extra equipment. The self-watering system is set manually or, alternatively, computer controlled to provide a water layer of between 0.5 — 1.0 mm thickness in front of the measuring wheel. A 400 L tank is built into the SFT and, between refills, is sufficient for a 5 000 m measuring run with 1.0 mm water layer. The watering system can operate at speeds up to at least 130 km/h.

5.12.9 The SFT can be calibrated and operated by a single operator. Automatic speed control can be provided.

5.12.10 Main characteristics of the tire are:

Dimension	400-8
Inflation pressure	700 kPa
Rubber compound	Based on natural rubber
Tread	Circumferential grooves
Structural design	Soft sidewalls

For runway calibration a friction measuring tire has been found to give a good correlation to certain other measuring equipment based on the yawed wheel principle.

Chapter 6

Collection and Dissemination of Pavement Surface State Information

6.1 GENERAL

6.1.1 The provisions in Annex 14, Chapter 2, 2.8 require that the appropriate authority assess the conditions of pavements whenever it has not been possible to clear the contaminants fully, and to make this information available to the appropriate units at the airport. Further, in accordance with the provisions in Annex 15, 5.1.1.1, a NOTAM notifying the presence or removal of hazardous conditions due to snow, slush, ice or water on the movement area must be issued. This information may be promulgated by means of a SNOWTAM (Figure 6-1).

6.1.2 The requirements for an effective system of collecting and disseminating pavement surface state information may be set out as follows (it is assumed that it is not always possible to achieve and maintain a clean, dry pavement surface).

6.1.3 The information gathered must be considered as part of a description of the state of all aspects of an airport, its aids and operational facilities which need to be known to the pilot before take-off or landing. In many cases, an adverse combination of available take-off or landing distance, tail or side wind components, visibility and poor friction characteristics will make a take-off or landing quite impossible.

6.1.4 In order to enable aircraft operators and pilots to readily appraise and use the information received, it is necessary to have the information and its presentation standardized. Furthermore, it must be in the form of a positive statement. Reports must also be as complete as possible. This, in turn, generates a mass of facts and, therefore, a standardized code is necessary in order to streamline the communications processes, particularly when severe meteorological conditions prevail over a large area. Rapid updating must also be available.

6.1.5 Data collection must be swift, comprehensive and accurate, and accuracy necessarily calls for special aids or instruments for the measurement of the different parameters so as to avoid subjective judgements.

6.1.6 Transmission of the information must be quick, regular and timely, i.e. it must reach the pilot in time to be of use and yet be up to date. This aspect is especially important as much of the information is necessarily very transitory.

6.1.7 Guidance on the notification, through NOTAM and Aeronautical Information Publications (AIP), of measures taken to maintain an airport in a satisfactory condition for flight operations, as required by Annex 15 (5.1.1.1 f), 5.1.1.5, 5.5.4, 2.0 5) of Appendix 1 and Appendix 2), is given in the *Aeronautical Information Services Manual* (Doc 8126-AN/872), Chapter 4 and Appendix A. An example of the type of information to be published in NOTAM Class II and AIP by a State is given in the AIS Manual, Appendix G.

6.2 WET SURFACE STATE INFORMATION

6.2.1 As explained earlier the runway should be periodically tested to ensure that its friction characteristics are above an acceptable level. In addition, runways with friction characteristics below the minimum acceptable level should be identified and pilots informed accordingly. To this end, the criteria used by the State for evaluating the runway surface friction characteristics should be published in the State Aeronautical Information Publication. This should include the time interval between measurements, the type of test device used and the minimum acceptable level selected by the State.

6.2.2 A NOTAM should be issued whenever the runway surface friction characteristics are found not to meet the minimum acceptable level selected by the State. The NOTAM should be issued until such time as corrective action has been taken by the State.

6.2.3 The calibration number(s) of the runway surface friction of a wet runway should be published in the Aeronautical Information Publication. This value will be the average value for the entire runway and will be obtained when the runway is wet but clean. If the surface friction characteristics differ significantly along a major portion of the runway, a calibration number will be given for each portion of the runway. A portion of the runway in the order of 100 m long may be considered significant for maintenance or reporting action. Since the value(s) will deteriorate with time, the date of the test should also be reported. This information is considered of great value as it will give an over-all indication of the surface friction of a runway and because the portion of a runway between the touchdown zones is normally not affected by rubber build-up.

6.3 SNOW-, SLUSH- OR ICE-COVERED SURFACE STATE INFORMATION

6.3.1 For long- and medium-term planning, aircraft operators need to be able to assess the degree of regularity which can be expected at an airport in winter conditions. Airport authorities also need to define the relevant parameters for their own purposes. Therefore, the State and airport authorities must give a clear and accurate statement of their intentions regarding:

- allocation of responsibility
- methods of clearance (including chemicals used, if any)
- equipment to be used
- order of clearance priorities
- methods of measurement
- table of friction coefficients for snow- and ice-covered surfaces
- methods for improving braking action
- criteria for snow bank reporting
- availability of information and dissemination procedures
- local deviations from national practice

6.3.2 Some of this information is of a permanent character but some is liable to change from season to season. When preparing the plan, the airport authority must also consult the airport users (and air traffic services units where these are not part of the authority) paying particular attention to arranging for reasonably ready access to the runways by the snow clearing and braking action measuring teams.

Data collection procedures

6.3.3 There exists a variety of methods whereby the flow of information from the actual runway to the point of insertion on to the various channels of communication and finally to the pilot is ensured but there is no one method which can be singled out as being the most efficient. However, the essential ingredients of an efficient system are readily apparent. The airport authority should be responsible for the various measurements required and for reporting pavement state to the dissemination agencies, usually air traffic services units and aeronautical information service (AIS) units. In order to do this, there is a need for the formation of a data collection team (who may have other tasks at other times) supplied with good instruments and properly trained in their use, who may be rapidly alerted and deployed so that the work is done rapidly and accurately and is integrated with the requirements of air traffic and the snow clearance teams. Experience has shown that the longest delay in the dissemination of reports occurs between the time of measurement and the filing time of the NOTAM/SNOWTAM. Therefore, measurement should be so arranged that the most transitory item, the braking action, should be the last item to be acquired. Having collected the data, the information must all go to one central collation and clearing house on the airport, be reduced to the appropriate form for transmission with the minimum delay and then disseminated through the appropriate communication channel. The latter point will invariably mean that the information will have to be presented for at least two forms of use: one by the local air traffic service units and local pre-flight briefing (AIS) and the other for pre-flight briefing (and en-route updating where possible) of inbound aircraft.

6.3.4 The timing may often be dictated by the need to have the information available to inbound flights one hour before take-off from their departure airports. Alternatively, with technological developments, it appears that for use by local air traffic service units, the airport authority can discharge responsibility for the collection of some items of information by arranging for them to be gathered automatically and continuously and fed direct to the controller's desk (i.e. analogous to wind speed and direction indicators). Similarly, the use of radio or even telemetry techniques can be considered for transmitting information from the runway to the clearing house or the controller. Naturally, the organization must be such that the whole span of hours of operation of the airport can be adequately covered and also such that measurements can be repeated at frequent intervals, often every half-hour, to allow for significant variations in the more critical factors occurring over quite short periods of time. Finally, the information must be readily interpreted both in the briefing room and on the flight deck and this means a rapid, simple decoding system and final presentation in plain language.

6.4 SNOWTAM FORMAT

6.4.1 This information may be promulgated by means of a SNOWTAM Format (Figure 6-1). To facilitate the completion of the SNOWTAM Format, a concise text containing explanatory notes is published on the reverse side of the SNOWTAM Format (6.4.3). The explanatory notes include, *inter alia*, information on:

a) maximum period of validity of SNOWTAM;
b) information on what constitutes a significant change in runway conditions requiring the issuance of a new SNOWTAM;
c) the reporting of XX in Item G, mean depth for each third of the total runway length, if it is not measurable or operationally not significant;
d) abbreviations used to indicate the type of friction test device reported in Item H; and
e) reporting in Item T of runway contaminant coverage as well as the condition of that part of the runway not cleared.

6.4.2 Detailed guidance on completion of the SNOWTAM, as well as samples of the completed pro forma and its associated teletype messages, are given in 6.4.4.

6.4.3 The SNOWTAM Format should contain the following explanatory notes on the reverse side:

1. General

   a) When reporting on two or three runways transmit Column 1 down to and including Item P, then Column 2, then Column 3 (if appropriate) and finish with Items R, S and T.

   b) Items together with their indicator must be dropped completely, where no information is to be included.

   c) Metric units must be used and the unit of measurement not reported.

   d) The maximum validity of SNOWTAM is 24 hours. New SNOWTAM must be issued whenever there is a significant change in conditions. The following changes, relating to runway conditions are considered significant:

      1) a change in the coefficient of friction of about 0.05;
      2) changes in depth of deposit greater than the following:
      20 mm for dry snow, 10 mm for wet snow, 3 mm for slush;
      3) a change in the available length or width of a runway of 10 per cent or more;
      4) any change in the type of deposit or extent of coverage which requires reclassification in Items F or T of the SNOWTAM;
      5) when critical snow banks exist on one or both sides of the runway, any change in the height or distance from centre line;
      6) any change in the conspicuity of runway lighting caused by obscuring of the lights; and
      7) any other conditions known to be significant according to experience or local circumstances.

2. Item A — Aerodrome (4-letter location indicator).

3. Item B — 8-figure date/time group — giving day, month and time of observation in GMT; this item must always be completed.

4. Item C — Runway designators.

5. Item D — Cleared runway length in m, if less than published length (see item T for reporting on part of runway not cleared).

6. Item E — Cleared runway width in m, if less than published width; if offset left or right of centre line add "L" or "R", as viewed from the threshold having the lower runway designation number.

7. Item F — Deposit over total runway length as explained in SNOWTAM Format. Suitable combinations of these numbers may be used to indicate varying conditions over runway segments. If more than one deposit is present on the same portion of the runway, they should be reported in sequence from the top to the bottom. Drifts, depths of deposit appreciably greater than the average values or other significant characteristics of the deposits may be reported under item T in plain language.

8. Item G — Mean depth in mm deposit for each third of total runway length, or "XX" if not measurable or operationally not significant. The assessment to be made to an accuracy of 20 mm for dry snow, 10 mm for wet snow and 3 mm for slush.

9. Item H — Braking conditions on each third of the runway and measuring equipment.

SNOWTAM	Priority Indicator	ADDRESSES	
Date and Time of filing	Originator's Indicator	SNOW NOTAM ("S" SERIES) SERIAL NUMBER	NOTAM S

AERODROME	A					
DATE/TIME OF OBSERVATION *(Time of completion of measurement in GMT)*	B		B		B	
RUNWAY DESIGNATORS	C		C		C	
CLEARED RUNWAY LENGTH, IF LESS THAN PUBLISHED LENGTH *(m)*	D		D		D	
CLEARED RUNWAY WIDTH, IF LESS THAN PUBLISHED WIDTH *(m; if offset left or right of centre line add "L" or "R")*	E		E		E	
DEPOSITS OVER TOTAL RUNWAY LENGTH *(Observed on each third of the runway, starting from threshold having the lower runway designation number)* NIL – CLEAR AND DRY 1 – DAMP 2 – WET or water patches 3 – RIME OR FROST COVERED *(depth normally less than 1 mm)* 4 – DRY SNOW 5 – WET SNOW 6 – SLUSH 7 – ICE 8 – COMPACTED OR ROLLED SNOW 9 – FROZEN RUTS OR RIDGES	F		F		F	
MEAN DEPTH *(mm)* FOR EACH THIRD OF TOTAL RUNWAY LENGTH	G		G		G	
BRAKING ACTION ON EACH THIRD OF RUNWAY AND MEASURING EQUIPMENT MEASURED OR CALCULATED COEFFICIENT *or* ESTIMATED BRAKING ACTION 0.40 and above — GOOD – 5 0.39 to 0.36 — MEDIUM/GOOD – 4 0.35 to 0.30 — MEDIUM – 3 0.29 to 0.26 — MEDIUM/POOR – 2 0.25 and below — POOR – 1 9 – unreliable — UNRELIABLE – 9 *(When quoting a measured coefficient use the observed two figures, followed by the abbreviation of the measuring equipment used. When quoting an estimate use single digits)*	H		H		H	
CRITICAL SNOWBANKS *(If present, insert height (cm)/distance from the edge of runway (m) followed by "L", "R" or "LR" if applicable)*	J		J		J	
RUNWAY LIGHTS *(If obscured, insert "YES" followed by "L", "R" or both "LR" if applicable)*	K		K		K	
FURTHER CLEARANCE *(If planned insert length (m)/width (m) to be cleared or if to full dimensions, insert "TOTAL")*	L		L		L	
FURTHER CLEARANCE EXPECTED TO BE COMPLETED BY . . . *(GMT)*	M		M		M	
TAXIWAY *(If no appropriate taxiway is available, insert "NO")*	N		N		N	
TAXIWAY SNOWBANKS *(If more than 60 cm, insert "YES" followed by distance apart, m)*	P		P		P	
APRON *(If unusable insert "NO")*	R					
NEXT PLANNED OBSERVATION/MEASUREMENT IS FOR . . . *(day/month/hour in GMT)*	S					
PLAIN LANGUAGE REMARKS *(Including contaminant coverage and other operationally significant information, e.g. sanding, deicing)*	T					

SIGNATURE OF ORIGINATOR *(not for transmission)*

Figure 6.1. SNOWTAM Format

Measured or calculated co-efficient (two digits) or, if not available, estimated braking action (single digit) in the order from the threshold having the lower runway designation number. Insert a code 9 when surface conditions or available measuring equipment do not permit a reliable braking action measurement to be made. Use the following abbreviations to indicate the type of measuring equipment used:

DBV	Diagonal braked vehicle
JBD	James Brake Decelerometer
MUM	Mu-meter
SFT	Surface Friction Tester
SKH	Skiddometer (high pressure tire)
SKL	Skiddometer (low pressure tire)
TAP	Tapley-Meter

If other equipment used specify in plain language.

10. Item J — Critical snowbanks. If present, insert height in cm and distance from edge of runway in m followed by Left ("L") or Right ("R") side or both sides ("LR"), as viewed from the threshold having the lower runway designation number, by height in cm and distance from edge of runway in m.

11. Item K — If runway lights are obscured insert "yes" followed by "L", "R" or both "LR" as viewed from the threshold having the lower runway designation number.

12. Item L — When further clearance will be undertaken, enter length and width of runway or "TOTAL" if runway will be cleared to full dimensions.

13. Item M — Enter the anticipated time of completion in GMT.

14. Item N — The code for Item F may be used to describe taxiway conditions;
Enter "NO" if no taxiways serving the associated runway are available.

15. Item P — If applicable, enter "yes" followed by the lateral distance in m.

16. Item R — The code for Item F may be used to describe apron conditions;
Enter "NO" if apron unusable.

17. Item S — Enter the anticipated time of next observation/measurement in GMT.

18. Item T — Describe in plain language any operationally significant information but always report on length of uncleared runway (Item D) and extent of runway contamination (Item F) in accordance with the following scale:

runway contamination:

10% - if less than 10% of runway contaminated
25% - if 11-25% of runway contaminated
50% - if 26-50% of runway contaminated
100% - if 51-100% of runway contaminated.

GUIDANCE FOR COMPLETION OF THE SNOWTAM FORMAT

6.4.4 The following material provides further guidance for the completion of the SNOWTAM Format:

General Comments

1. When reporting on more than one runway use the second and third columns, as applicable.

2. The codes for Item F may be used for describing conditions on taxiways and aprons.

3. Metric units must be used and the unit of measurement not reported. Include unit of measurement in Item T, if needed for clarification.

4. The maximum validity of SNOWTAM is 24 hours. New SNOWTAM must be issued whenever there is a significant change in conditions. The following changes relating to runway conditions are considered as significant:

a) a change in the coefficient of friction of about 0.05;
b) changes in depth of deposit greater than the following:
   20 mm for dry snow; 10 mm for wet snow; 3 mm for slush;
c) a change in the available length or width of a runway of 10 per cent or more;
d) any change in the type of deposit or extent of coverage which requires reclassification in Items F or T of the SNOWTAM;

e) when critical snow banks exist on one or both sides of the runway, any change in the height or distance from centre line;
f) any change in the conspicuity of runway lighting caused by obscuring of the lights; and
g) any other conditions known to be significant according to experience or local circumstances.

Specific comments for each item

Item A — enter the 4-letter location indicator for the aerodrome.

Item B — enter the date the assessment was made by giving an 8-digit date-time group indicating the day, month and Greenwich Mean Time (GMT) of the observation, (e.g. 01020850, meaning 1 February at 0850 GMT). This time may differ for different runways and the 8-digit date-time should be entered for each runway.

Item C — enter the runway designation numbers, e.g. 16/34.

Item D — enter the length of runway cleared of snow in metres if this is less than the published length, e.g. 3 300. (See Item T).

Item E — enter the runway width cleared of snow if this is less than the published width, in metres. If this width is offset from the runway centre line, as viewed from the threshold having the lower runway designation number, enter "L" after the unit of measurement if it is offset to the left or "R" if it is offset to the right, e.g. 40 L.

Item F — describe the runway surface condition for each third of the runway by reporting the appropriate code number shown on the form that best describes the condition. The order of reporting should be from the threshold having the lower runway designation number, e.g. 4/5/4. Suitable combinations of numbers may be used to indicate varying conditions over runway segments. If more than one deposit is present on the same portion of the runway they should be reported in sequence from the top to the bottom of the total deposit, e.g. 57/56/57. Drifts, depths of deposit appreciably greater than the average values or other significant characteristics of the deposits may be reported under Item T in plain language. If a damp condition is reported then the reason for this should be clarified in Item T.

Item G — report the mean depth in millimetres of any dry snow, wet snow or slush identified in Item F on any one-third of the runway in the same order as reported for Item F. The assessment of the depth of deposit should be made to an accuracy of approximately 20 mm for dry snow, 10 mm for wet snow and 3 mm for slush. If mean depth is not measurable or operationally not significant, a code "XX" should be reported, e.g. 20/10/XX.

Item H — enter the assessment of the braking action on each third of the runway in the same order as for Item F and the type of measuring equipment used if appropriate. When measuring equipment is used, the measured braking coefficient should be reported and no descriptive assessment (i.e. good, poor, etc.) given. When measuring equipment is not used, the most appropriate descriptive assessment as shown on the form should be entered. If measuring equipment does not permit measurement of friction with satisfactory reliability, which may be the case when a runway is contaminated by slush or loose snow, a code 9 should be reported.

Use the following abbreviations to indicate the type of measuring equipment used:

DBV	Diagonal braked vehicle
JBD	James Brake Decelerometer
MUM	Mu-meter
SFT	Friction tester
SKH	Skiddometer (high pressure tire)
SKL	Skiddometer (low pressure tire)
TAP	Tapley-Meter

If another type of equipment is used then specify in plain language.

Item J — when critical snowbanks are present as defined in the State AIP enter the height in centimetres and distance in metres from the edge of the runway. Also indicate if they are to the left ("L") or right ("R") as viewed from the threshold having the lower runway designation number or on both sides ("LR"), e.g. 30/5 L.

Item K — when runway lights are obscured enter "YES" followed by "L", "R" or both "LR" if applicable, as viewed from the threshold having the lower runway designation number, e.g. Yes L.

Item L — when further clearance of the runway beyond that reported in item D or E is anticipated enter the length/width in metres anticipated to be cleared, e.g. 2500/35. If it is intended to clear the total runway, enter 'TOTAL'.

Example No. 1

SNOWTAM	**Priority Indicator** GG	**ADDRESSES** EDZZSA LIZZSA ABZZSC	
Date and Time of filing 01 02 0930	**Originator's Indicator** EALLYN	**SNOW NOTAM ("S" SERIES) SERIAL NUMBER** 279	**NOTAM** S

AERODROME	A	EACD				
DATE/TIME OF OBSERVATION *(Time of completion of measurement in GMT)*	B	01020850	B	01020905	B	
RUNWAY DESIGNATORS	C	16/34	C	07/25	C	
CLEARED RUNWAY LENGTH, IF LESS THAN PUBLISHED LENGTH *(m)*	D	3300	D	—	D	
CLEARED RUNWAY WIDTH, IF LESS THAN PUBLISHED WIDTH *(m; if offset left or right of centre line add "L" or "R")*	E	40L	E	—	E	
DEPOSITS OVER TOTAL RUNWAY LENGTH *(Observed on each third of the runway, starting from threshold having the lower runway designation number)* NIL – CLEAR AND DRY 1 – DAMP 2 – WET or water patches 3 – RIME OR FROST COVERED *(depth normally less than 1 mm)* 4 – DRY SNOW 5 – WET SNOW 6 – SLUSH 7 – ICE 8 – COMPACTED OR ROLLED SNOW 9 – FROZEN RUTS OR RIDGES	F	4/5/4	F	57/56/57	F	
MEAN DEPTH *(mm)* FOR EACH THIRD OF TOTAL RUNWAY LENGTH	G	20/10/20	G	05/05/05	G	
BRAKING ACTION ON EACH THIRD OF RUNWAY AND MEASURING EQUIPMENT MEASURED OR CALCULATED COEFFICIENT *or* ESTIMATED BRAKING ACTION 0.40 and above — GOOD – 5 0.39 to 0.36 — MEDIUM/GOOD – 4 0.35 to 0.30 — MEDIUM – 3 0.29 to 0.26 — MEDIUM/POOR – 2 0.25 and below — POOR – 1 9 – unreliable — UNRELIABLE – 9 *(When quoting a measured coefficient use the observed two figures, followed by the abbreviation of the measuring equipment used. When quoting an estimate use single digits)*	H	30/35/30 MUM	H	32/36/9 MUM	H	
CRITICAL SNOWBANKS *(If present, insert height (cm)/distance from the edge of runway (m) followed by "L", "R" or "LR" if applicable)*	J	30/5 L	J	—	J	
RUNWAY LIGHTS *(If obscured, insert "YES" followed by "L", "R" or both "LR" if applicable)*	K	YES L	K	—	K	
FURTHER CLEARANCE *(If planned insert length (m)/width (m) to be cleared or if to full dimensions, insert "TOTAL")*	L	TOTAL	L	—	L	
FURTHER CLEARANCE EXPECTED TO BE COMPLETED BY . . . *(GMT)*	M	1300	M	—	M	
TAXIWAY *(If no appropriate taxiway is available, insert "NO")*	N	NO	N	—	N	
TAXIWAY SNOWBANKS *(If more than 60 cm, insert "YES" followed by distance apart, m)*	P	YES 10	P	—	P	
APRON *(If unusable insert "NO")*	R					
NEXT PLANNED OBSERVATION/MEASUREMENT IS FOR . . . *(day/month/hour in GMT)*	S	01021400				
PLAIN LANGUAGE REMARKS *(Including contaminant coverage and other operationally significant information, e.g. sanding, deicing)*	T	RWY 07 SANDED, LAST 300 M RWY 16 COVERED BY 50 MM SNOW				
RWY CONTAMINATION 100 % BOTH RWYS						

SIGNATURE OF ORIGINATOR *(not for transmission)*

Item M — enter the anticipated Greenwich Mean Time for completion of the action described in item L, e.g. 1300.

Item N — if no taxiways serving the associated runway are available, enter 'NO'.

Item P — if snowbanks exist alongside the taxiways serving the runway and they are more than 60 cm high, enter "YES", followed by the lateral distance in metres, e.g. YES 10.

Item R — if the apron is not usable enter "NO".

Item S — enter the anticipated day, month and time of next observation/measurement in GMT, e.g. 01021400.

Item T - use this field to describe, in plain language, contaminant coverage and any other operationally significant information such as the corrective action of sanding, gritting, or de-icing, e.g. RWY 07 sanded. If cleared runway length is less than published length, specify the conditions on that part of the runway not cleared, e.g. last 300 m of RWY 16 covered by 50 mm snow. When a runway is contaminated, the following should be reported for each third of the runway as appropriate:

runway contamination:

10% - if less than 10% of runway is contaminated
25% - if 11-25% of runway is contaminated
50% - if 26-50% of runway is contaminated
100% - if more than 50% of runway is contaminated

If a damp condition has been reported then it should be indicated if this is a natural condition, e.g. "Runway 16 dampness natural". Alternatively, if the dampness is due to application of chemicals to prevent or remove ice then the report should be "Runway 16 dampness due to chemicals".

SNOWTAM SAMPLE

Samples of a completed format and its associated teletype message are given in Examples Nos. 1 and 2, respectively.

Example No. 2

GG EDZZSA LIZZSA ABZZSC
01020930 EALLYN
NOTAM S 279

A) EACD B) 01020850 C) 16/34 D) 3300
E) 40L F) 4/5/4 G) 20/10/20 H) 30/35/30 MUM
J) 30/5 L K) YES L L) TOTAL M) 1300 N) NO
P) YES 10 B) 01020905 C) 07/25 F) 57/56/57
G) 05/05/05 H) 32/35/9 MUM S) 01021400
T) RWY 07 SANDED LAST 300 M RWY 16
COVERED BY 50 MM SNOW, RWY
CONTAMINATION 100% BOTH RWYS

Chapter 7

Snow Removal and Ice Control

7.1 GENERAL

7.1.1 It is impossible to decide, in advance, on the measures that should be adopted in order to improve the friction coefficient (μ value) on a movement area where ice, snow, slush, water and other contaminants result in impaired friction characteristics since, at a particular airport, the meteorological conditions can lead to a great variety of situations demanding entirely different countermeasures. A combination of measures adapted to the equipment available at that airport will, therefore, have to be decided upon in every single case.

7.1.2 There are weather conditions which can lead to situations presenting difficult problems to the personnel because the equipment which would meet the case most effectively is not available (perhaps it has not even been manufactured), or the situation may require so much labour, time and money that no more than a slight improvement in the low friction coefficient can be achieved. Perhaps efforts have to be concentrated on maintaining the present value of the friction coefficient. Such unfavourable meteorological conditions exist, for example, when:

a) freezing rain is continuing to fall;
b) an ice-crust is still forming;
c) there is a sudden lowering of the temperature in the top layer of the pavement owing to heat radiation, which turns the moisture on the pavement surface into ice; or
d) there are sudden changes in temperature about freezing point while it is raining or snowing.

7.1.3 In practice, the variations in the weather situation at a given airport demand a professional evaluation of the combination "weather-measure-equipment" and the choice of equipment suitable for such an evaluation. It is the situation facing any qualified worker who, among a great many tools in his tool-chest, has to choose the one that is specially suitable for the work in hand.

7.1.4 Whatever technique may be employed for the removal of snow, slush, ice and standing water, the aim must be to speedily and cleanly restore the movement area and facilities to the highest degree of serviceability. Only in providing a continuously safe operating surface for aircraft can the efficient and economical commerce of air transportation be assured. This criterion seems applicable to all airports, regardless of size or the density of operation they support.

7.1.5 Clearance of snow, slush, ice and standing water from the movement area should be based on flight safety and schedule considerations. Normally, this will lead to the following priority:

a) runway(s) in use;
b) taxiways serving runway(s) in use;
c) apron(s);
d) holding bays;
e) other areas.

7.1.6 It is recognized that airport operating authorities throughout the world have developed their own equipment and techniques to effect the clearance and removal of contaminants. Although equipment combinations and techniques of application vary, the objective to speedily provide clean and dry airport pavements is constant.

7.1.7 There are many factors to be considered when determining the equipment necessary for the removal of surface contaminants encountered on airports pavements. Topography, climate, airport location, type of aircraft, density of movements, characteristics of operating surfaces and navigational facilities are but a few of the considerations.

7.1.8 Airports located in tropical or sub-tropical zones may be concerned with problems associated with heavy and frequent rain squalls leading to standing water clearance. Again, depending upon their locale and the flying activity, rubber, sand, dust and mud deposits are common to many tropical and temperate zone airports. In the more northerly latitudes, snow, slush and ice removal involves the continuous commitment of manpower and equipment resources for several months of the year and a significant portion of the airport authority's operating budget.

APPENDIX B

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ICAO AIRWORTHINESS TECHNICAL MANUAL

PART III

SECTION 8: OPERATING LIMITATIONS AND INFORMATION

AIRWORTHINESS TECHNICAL MANUAL

PART III

SECTION 8. OPERATING LIMITATIONS AND INFORMATION

Section 8

Operating Limitations and Information

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SECTION 8

INTRODUCTORY NOTES

Chapter 1. Operational measures for dealing with the problem of taking off from slush- or water-covered runways

1. The guidance material in this chapter is based on the specifications developed by the Airworthiness Committee and issued as ICAO Circular 60 and Amendment 1.

2. The Air Navigation Commission, after satisfying itself that the guidance material in this chapter had been properly co-ordinated with the ICAO Standards and that the policies of the Organization had been followed, agreed to its issuance at the 3rd Meeting of its 72nd Session on 8 February 1973.

3. The Airworthiness Committee at its Fourteenth Meeting held in October-November 1981 developed Recommendation 9/1 to include in the chapter an analytical method of estimating aircraft rolling resistance in loose, dry snow. The Air Navigation Commission at the 24th Meeting of its 98th Session noted this recommendation and requested the Secretary General to incorporate the material together with editorial changes, as necessary, in the manual. An opportunity was also taken to convert all units to the International System of Units (SI) in conformity with the provisions of Annex 5. As a result of all the above-mentioned changes, this chapter was reissued.

Chapter 1

Operational Measures for Dealing with the Problem of Taking Off from Slush-[1] or Water-covered Runways

1. INTRODUCTION

1.1 There are a number of problem areas in the operation of civil transport aeroplanes which, although they existed for piston-engined types, have become acute only with the introduction of turbine-engined aeroplanes. Not the least of these is associated with operations from slush-covered runways.

1.2 There are three operational problems which arise when operating from slush-covered runways: first, that relating to take-off where the distance required for take-off is increased due to slush drag, second, that relating chiefly to take-off where slush spray thrown up by the wheels enters engine intakes causing serious loss of thrust or even complete stoppage of the engine, with consequent loss of performance, and third, those relating to both take-off and landing where, due to reduced friction between tires and runway, there is reduced directional control and also reduced braking friction causing increased distances required for landing and for abandoned take-off. The purpose of this chapter is chiefly to deal with the first of these problems although some mention is made of the second.

1.3 In determining the effects of slush on an aeroplane during take-off, there are a number of aspects of the problem to be considered:

a) the effect on aeroplane performance due to:

   1) retardation effects on aeroplane wheels running through the slush layer, and

   2) drag due to impingement on the aeroplane of spray thrown up by the wheels;

b) the possibility of structural damage due to spray impingement;

c) the possibility of power loss or system malfunction due to spray ingestion;

d) the possibility of jammed landing gear due to filling of wheel wells with slush followed by freezing; and

e) the possibility of wing flaps becoming inoperative due to accumulated slush.

1.4 The characteristics of turbine-engined aeroplanes which tend to make the problem more acute than for piston-engined aeroplanes are:

a) higher take-off ground speeds, making the presence of slush on the runway much more significant from drag and damage considerations;

b) increased sensitivity of take-off performance to drag increments due to:

   1) a greater portion of the take-off distance being spent on the ground, and

   2) the marked diminution in excess thrust which results from any attempt to lift off at speeds below the normal values;

c) lower wing and engine height in relation to aeroplane length, resulting in increased susceptibility to ingestion and impingement damage;

d) a tendency to operate from runways of critical length on a higher percentage of occasions.

1.5 The need to minimize ingestion effects and impingement damage will tend to impose upper limits on slush depths, whereas considerations of performance will tend to permit take-off in a range of slush conditions depending on take-off distance available.

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[1] Throughout this chapter the term "slush" is used to cover the whole range of precipitation densities from that of dry snow to that of free-standing water.

1.6 This chapter also includes currently available data which lead to a more complete understanding of the problem, and suggests procedures in both the airworthiness and operations fields which will lead to effective control of the risk level associated with take-off from precipitation-covered runways.

2. ENGINE INGESTION PROBLEMS

2.1 Considerable attention has been paid by manufacturers, operators and airworthiness authorities to the problem of ingestion of slush during take-off.

2.2 The consequence of this activity has been that either most recent transport aeroplanes have been demonstrated to be free of ingestion troubles, or operating techniques have been developed which avoid any serious difficulty.

Note.— See Appendix A for extracts from U.S. and U.K. Airworthiness Requirements.

3. THE EFFECT OF SLUSH ON TAKE-OFF PERFORMANCE

3.1 Typical increments to the take-off ground roll of a jet transport aeroplane are given in Table 1. The assumptions made in the estimation of these increments are discussed in Appendix B which indicates a method for estimating the effect of slush on take-off performance.

Note.— While the method of Appendix B allows the estimation of these effects at any slush depth or density, some operators may prefer, in view of the difficulties of assessing the values of the depth or density accurately, to calculate the effects for only one or two critical values, for example:

Depth: *For the limiting depth of slush or water for the aeroplane under consideration; this effect might then be used for all lesser depths.*

Density: *For one density in the dry snow range of possible densities, and one density in the slush/water range of possible densities. In each case, the worst density in the particular density range would have to be determined and used. Owing to the effects of aquaplaning, this might not be the highest density in the range of possible densities.*

Table 1. Percentage increase in ground roll

Slush depth (mm)	*Thrust/mass ratio (N/kg)*	
	3	2
10	18	22
20	48	64

3.2 The discussion in Appendix B will illustrate the marked effect that a number of parameters can have on the performance effects of slush. Thus the figures quoted in Table 1 should be treated as a rough guide only.

3.3 Although Appendix B gives an outline of methods which can be used for estimating the effect of slush on take-off performance, operators may have difficulty in obtaining the basic aerodynamic data of their aeroplanes in sufficient detail to enable them to make performance estimates.

Note.— In the United States a Federal Aviation Administration Advisory Circular[2] states that: "the operations manual should include specific instructions for the flight crew on each type of turbojet aircraft showing the gross weight reduction, V_1 speed adjustment, and/or additional runway length required for the conditions described." The United Kingdom Civil Airworthiness Requirements[2] specify requirements for the determination and scheduling in the aeroplane flight manual of the effect of precipitation on take-off performance. Thus, in cases where an aeroplane is manufactured or operated in either the United States or the United Kingdom, it may be possible to obtain suitable information on slush performance effects from the operators or manufacturers in those countries.

3.4 Clearly the most accurate information which can be given for the performance effect of slush is that which has been accurately measured on the particular aeroplane. Appendix C gives an outline of test methods which have been used for this purpose.

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[2] See Appendix A for extracts from United States and United Kingdom airworthiness requirements.

3.5 An analytical method of estimating rolling resistance of aircraft in loose dry snow is given in Appendix D.

4. CLEARANCE AND PREVENTION OF BUILD-UP

4.1 The goal of aerodrome authorities should be the complete removal of precipitation from runways. To some extent a build-up of precipitation can be "designed out" by adopting appropriate runway construction techniques such as grooving, porous surface, adequate crossfall, good drainage, etc. Where this has not been done or where the rate of precipitation is so high that some accumulation still occurs, rapid clearance action should be taken, particularly in the case of snow or slush. Since it is now thought that aquaplaning and hence braking and control problems can occur in slush or water depths as low as 1 mm, it is desirable that aerodrome equipment should be capable of clearing the runway down to the runway surface. To achieve this, speed is essential since it is particularly important to prevent snow becoming impacted by traffic. Consequently, there appears to be a need for equipment that can move rapidly and in sufficient numbers to clear an adequate width of runway in one operation. The equipment should be in action during the snowfall as frequently as traffic permits.

4.2 Clearance should be carried out over the complete length of the runway to a width of at least 30 m for runways up to 2 100 m long in conditions of favourable winds and visibilities. For longer runways and less favourable conditions the clearance width should be at least 36 m. In both cases, the area of clearance should be increased to 45 m as soon as possible after initial clearance.

4.3 Experience has shown that the most effective equipment for clearing down to the runway surface is that having a brush in combination with a blower. Some research into the use of a mechanical squeegee is being undertaken and this could prove useful for clearing small depths of water or wet slush.

4.4 The clearance procedure must not result in any significant walls at the side of the swept area in view of the hazard to aeroplanes which this will create if the surface is slippery, and particularly when crosswinds exist. Aerodrome authorities should be provided with advice on the maximum acceptable heights of snow banks which may be permitted for the most limiting aeroplane type using the airfield.

5. MEASUREMENT

5.1 It may be many years before the ideal of completely cleared runways is achieved in all States. Those States which do not have the facilities to achieve cleared runways will need to provide a measuring and reporting service to enable compliance with Chapter 5 of Annex 6, Part I. This calls for account to be taken of the effects of snow, slush, ice and water on aeroplane performance.

5.2 In the case of snow and slush, operators will require information on depth and density of the precipitation. At present, measurement of snow and slush depth is largely made by using a calibrated dip stick and a subjective assessment of density is also given. Because of variation in depth along runways, it is usual to take measurements at about 300 m intervals along the runway on either side of the centre line. A more sophisticated type of equipment, which has been undergoing operational trials, provides a mean drag figure for the usable length of runway. To overcome variations due to depth, density and properties of the precipitation, the equipment has been calibrated to indicate the equivalent depth of water so as to provide measurements in terms of a medium of known density and physical properties. It is hoped to develop a further refinement which will provide the actual depth of the deposit and so enable a realistic density to be determined. At present this information is only available by subjective assessment.

5.3 In the case of water, some estimate of depth will be required by operators. This information should also take account of significant ponding on otherwise dry runways.

5.4 For water depth measurement, trials are being conducted in one State with precise depth gauges let into the runway surface. Depths as low as 1 mm can be recorded with this device which automatically reports and records in the control tower. Where precise methods of water depth measurement are not used, a subjective assessment of the degree of wetness on the runway should be provided, together with general advice on precipitation rates, i.e. heavy rain, drizzle, etc.

5.5 Ice depth is not measured since the effect on performance of such contamination does not vary with depth.

6. REPORTING NOTIFICATION AND ACTION TO BE TAKEN

6.1 A procedure[3] has been developed for the reporting of the runway state and significant changes thereto. Notification is made by SNOWTAM and the action required is described in Annex 15. It is not normal for rainfall, i.e. water depth information, to be included in such reports.

6.2 It is desirable that the depth of snow or slush should be reported. The report should be indicative of the situation on the runway as a whole.

Note.— When the influence of density on take-off performance is known (see Appendix B, Figure 5A), aerodrome authorities are encouraged to report density, even if only in subjective terms.

6.3 The presence of ice or ice patches should be reported.

6.4 Information on water depth should be given in subjective terms if actual depth measurement is not available, i.e. damp, very wet, etc. Ponding where present should also be notified. In order to give pilots some indication of the likely change of runway state, broad information on rainfall rate or expected rate should be provided.

6.5 A flight should not be commenced when the runway is covered with slush unless an assessment of the performance of the aircraft in prevailing conditions shows that the available performance is adequate.

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[3] This procedure has now been incorporated in Annex 15 and as such applies on a world-wide basis.

Appendix A

Airworthiness Requirements Relating to Operations in Slush Published in the United States and the United Kingdom

A. EXTRACTS FROM FEDERAL AVIATION ADMINISTRATION ADVISORY CIRCULAR NO. AC91-6A

(Note.— Conversions to SI units have been inserted by ICAO)

Subject: Water, Slush and Snow on the Runway

"4. *Guidelines and recommendations*

The following guidelines and recommendations are provided for those situations where an aircraft takes off on runways with standing water, slush, and/or snow:

a) Take-offs should not be attempted when standing water, slush, or wet snow greater than 12 mm (0.5 in) in depth covers an appreciable part of the runway.

b) The Federal Aviation Regulations concerned with an aircraft's take-off and landing performance and airplane flight manual requirements are predicated on clean, dry runways. Therefore, certain adjustment factors should be applied to the take-off data when operating in wet snow, slush, or standing water in depths up to 12 mm (0.5 in).

c) The operations manual of the air carrier and commercial operator or other appropriate documents for general aviation aircraft should include specific instructions for the flight crew on each type of turbojet aircraft showing the gross weight reduction, V_1 speed adjustments, and/or additional runway length required for the conditions described. These instructions should outline details of the methods to be used in determining runway conditions at departure time."

B. EXTRACT FROM FEDERAL AVIATION REGULATION NO. 25

25.1091. *Air Induction*

"d) For turbine engine powered airplanes and airplanes incorporating auxiliary power units —

. . .

2) The airplane must be designed to prevent water or slush on the runway, taxiway, or other airport operating surfaces from being directed into the engine or auxiliary power unit inlet ducts in hazardous quantities, and the air inlet ducts must be located or protected so as to minimize the ingestion of foreign matter during take-off, landing, and taxiing."

C. EXTRACT FROM UNITED KINGDOM CIVIL AIRWORTHINESS REQUIREMENTS SECTION D

Chapter D2-2. Appendix

"1.6.4 Where certification for take-off from precipitation-covered runways is sought, the Take-off Run Required and Take-Off Distance Required appropriate to these conditions should be determined and scheduled in accordance with D2-3, 4.1.1. The data should cover a range of relative precipitation densities from 0.2 to 1.0.

Notes:

1) Compliance with D2-7, 3.3 and D5-5, 1.3.1 will also have to be shown.

2) The Flight Manual will state whether or not take-off from precipitation-covered runways is permissible.

3) Any special aeroplane handling techniques necessary to ensure compliance should still comply with D2-2, 6.4.

4) It will not usually be acceptable for data obtained by means of tests in water or other high density precipitation to be extrapolated to a precipitation depth in excess of 50 mm (2 in); e.g. for depths of dry snow greater than 50 mm (2 in) direct evidence of the performance will be required.

5) The data may be expressed in terms of equivalent depth of water provided that the favourable effects *of aquaplaning are not assumed to occur below the aquaplaning speed for the lowest density of slush for which data are available.*

6) Acceptable methods for simulating precipitation-covered runways should be agreed with the Board."

Chapter D2-3

"4.1.1 *Precipitation on runways.* The Take-Off Run Required and Take-Off Distance Required appropriate to take-off from precipitation-covered runways shall be the all-power-units-operating Take-Off Run Required and the all-power-units-operating Take-off Distance Required respectively appropriate to the precipitation condition, and shall be determined in accordance with 5(a) and 6.1(a)."

Chapter D2-7

"3.3 *Precipitation on runways.* Where certification for take-off from precipitation-covered runways is sought (see D2-2, App. No. 1, 1.6.4), a technique for such take-offs, compatible with D5-5, 1.3, shall be established. It shall be demonstrated that the technique is such that when the aeroplane is taking off in precipitation depths up to the maximum for which take-off data are to be scheduled, there is:

a) no damage to parts of the aeroplane such as would adversely affect airworthiness, and

b) no accumulation of precipitation on or in parts of the aeroplane which could cause immediate or subsequent hazard, e.g. loss of control or inability to change configuration, subsequent ingestion by the power-units of hazardous quantities of accumulated slush which become detached from the aeroplane.

Note.— Any special aeroplane handling techniques necessary to ensure compliance with this requirement should still comply with D-2, 6.4."

Chapter D5-5

"2.2 *Take-off from precipitation-covered runways.* Except where it is obvious, by inspection or other means, that precipitation on the runway would not enter engine air intakes during the take-off run, compliance shall be shown with the requirements of 2.2.1 or 2.2.2, as appropriate.

2.2.1 *Aeroplane certificated for take-off from precipitation-covered runways.* It shall be demonstrated that when the aeroplane is taking off and traverses areas of precipitation up to whichever is the greater of 19 mm (0.75 in) depth or the precipitation depth for which take-off data are to be scheduled, the power-units operate satisfactorily without unacceptable loss of power at all aeroplane speeds up to that at which the transition to climbing flight is completed and in the attitudes likely to be used in this speed range (see also D2-2, App. No. 1, 1.6). Compliance with this requirement may be shown either by means of complete take-offs in the specified precipitation conditions or by means of a series of demonstrations in areas of precipitation, the length of which is agreed by the Board to be sufficient both to determine the effects on aeroplane performance and on engine behaviour and response, and to establish the stabilised spray pattern.

Note.— Any special aeroplane handling techniques necessary to ensure compliance with this requirement should still comply with D2-2, 6.4.

2.2.2 *Aeroplane not certificated for take-off from precipitation-covered runways.* It shall be demonstrated that when the aeroplane is taking off and traverses areas of precipitation up to 19 mm (0.75 in) in depth and not less than 90 m (300 ft) in length in the direction of take-off, the power-units operate satisfactorily without unacceptable loss of power at all speeds up to that at which the transition to climbing flight is completed and in all attitudes likely to be used in the specified speed range.

Notes:

1) The Board should be consulted where there is difficulty in meeting this requirement, in which case the CAA may agree with the Applicant suitable operational limitations to ensure satisfactory operation from a runway on which there are areas of slush or water, even though the runway is nominally clear.

2) An aeroplane may be accepted as complying with this requirement even if the possibility of serious power reduction is found to exist in specific circumstances; for example, where the possibility of power reduction arises only at a point from which a take-off could safely be abandoned (even in adverse braking conditions) and no unacceptable damage is caused to the power-units."

Appendix B

Estimation of Performance Effects and Influence on Parameters

1. It is now well established that the drag due to slush may be expressed by the relationship (Reference 1):

$$D_S = C_{DS} \frac{\varrho_w \sigma_s}{2} V_g^2 d_s b$$

where:

D_S = total aeroplane retardation force due to slush

ϱ_w = density of water

σ_s = relative density of slush

V_g = aeroplane ground speed

d_s = slush depth

b = chord length of the tire cross-section at slush surface

C_{DS} = slush drag coefficient.

The product $d_s \sigma_s$ is frequently termed the "water equivalent depth" (W.E.D.) of slush.

2. The chord length of tire cross-section at the slush surface may be expressed approximately (Reference 1) as:

$$b = 2w \left[\frac{\delta + d_s}{w} - \left(\frac{\delta + d_s}{w} \right)^2 \right]^{1/2}$$

where:

w = maximum tire width

δ = vertical tire deflection.

3. The slush drag coefficient of an isolated single aeroplane wheel has been established by experiment (Reference 1) in both slush and water as close to 0.75. There is some evidence that in dry snow there is a significant reduction in drag coefficient due to the fact that the wheel does not remove all the snow from its path, as is the case for slush and water.

4. The presence of an undercarriage leg or additional wheels considerably modifies the isolated single wheel drag coefficient (Reference 2). For example, a dual-tandem (four-wheel-bogie) wheel arrangement enjoys reductions in drag from the favourable interference effect of side-by-side wheels and from the slush clearing effect of the leading wheels but suffers considerable losses due to spray impingement drag on the undercarriage leg.

5. Drag is generated by spray impingement on areas other than the undercarriage leg. Full-scale tests have shown that the spray from nose wheels impinging on the airframe, notably the flaps, can contribute a significant part of the total retarding force on the aeroplane (Reference 4). Where aeroplane geometry poses a spray impingement problem, some relief may be obtained by spray deflection using "chined" tires or spray drag alleviators (Reference 2).

6. The assumption that slush drag is proportional to (ground speed)^2 is valid until the aquaplaning speed is approached when the wheels begin to rise to near the top of the slush layer, supported by hydrodynamic forces (Reference 5). The aquaplaning speed is a function of a number of slush, tire and runway surface parameters but to a first approximation may be expressed, for water, (Reference 5) by:

$$V_p = 6.3 \sqrt{p}$$

where V_p is aquaplaning speed in km/h and p is tire inflation pressure in kPa

$$(\text{or } V_p = 3.4 \sqrt{p}$$

where V_p is aquaplaning speed in kt and p is tire inflation pressure in kPa).

7. If slush may be treated as an incompressible fluid, it is reasonable to assume that the aquaplaning speed in slush is given by:

$$V_p = 6.3\sqrt{\frac{p}{\sigma_s}}$$

where V_p is aquaplaning speed in km/h and p is tire inflation pressure in kPa

$$\text{(or } V_p = 3.4\sqrt{\frac{p}{\sigma_s}}$$

where V_p is aquaplaning speed in kt and p is tire inflation pressure in kPa; σ_s is relative density of slush).

Note.— Test confirmation of the above relationship is incomplete.

8. The onset of aquaplaning of main or nose wheels is accompanied by the start of a progressive reduction in the associated slush drag (References 6 and 7). The reduction is approximately proportional to (ground speed)^2. The small amount of full-scale testing at speeds well above the aquaplaning speed suggests that the slush drag coefficient reduces to zero at about 160 per cent to 180 per cent of the aquaplaning speed (References 3 and 6) although the controlling parameters are not well understood.

9. A somewhat idealized representation (Reference 6) of the slush drag or speed relationship for a typical large jet transport aeroplane is shown in Figures B1 a) and B1 b).

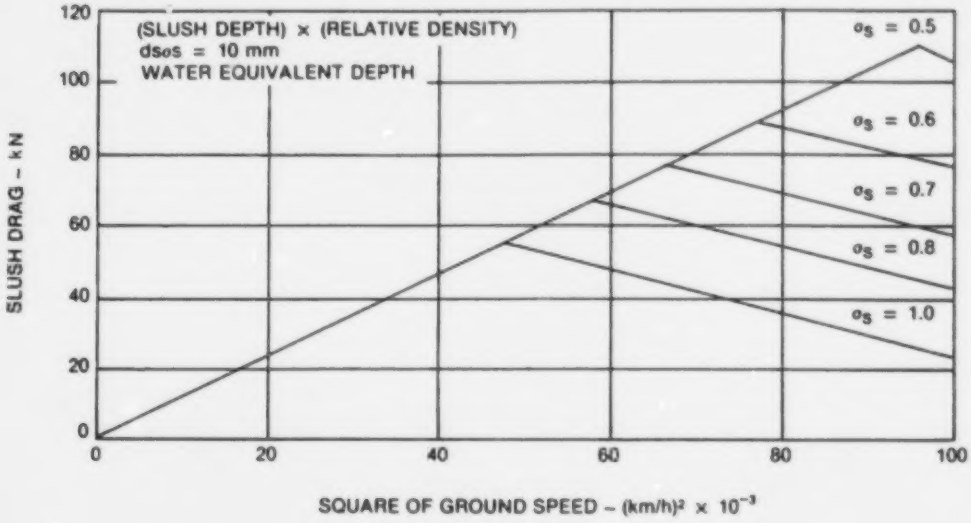

Figure B1 a) Effect of water equivalent depth on slush drag

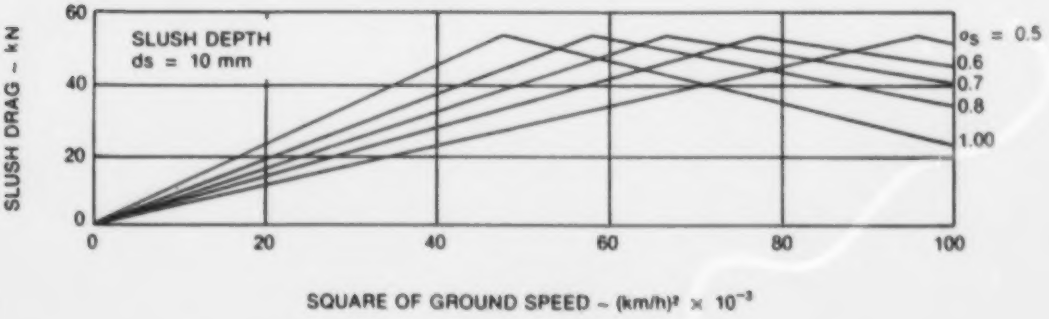

Figure B1 b) Effect of slush depth on slush drag

10. In order to illustrate the effects on take-off performance of a number of aeroplane and slush parameters, estimates of take-off ground roll for the typical jet transport aeroplane of Figures B1 a) and B1 b) have been made for ISA, sea-level, zero wind and level runway conditions. Other assumptions are as follows:

a) Net accelerating force in the absence of slush approximated by:

$$T - D = 267\,000 - 1.11\, V_g^2$$

where T and D are thrust and drag, respectively, in newtons and V_g is aeroplane ground speed in km/h

$$(\text{or: } T - D = 267\,000 - 3.81\, V_g^2$$

where V_g is aeroplane ground speed in kt).

b) Lift-off speed:

$$V_{LOF} = 298 \sqrt{\frac{M}{136\,000}}$$

where V_{LOF} is lift-off speed in km/h and M is aeroplane all-up mass in kg

$$(\text{or: } V_{LOF} = 161 \sqrt{\frac{M}{136\,000}}$$

where V_{LOF} is lift-off speed in kt).

c) Aquaplaning speed:

$$V_p = \frac{219.5}{\sqrt{\sigma_s}}$$

where V_p is aquaplaning speed in km/h and σ_s is relative density of slush

$$(\text{or: } V_p = \frac{118.5}{\sqrt{\sigma_s}}$$

where V_p is the aquaplaning speed in kt).

d) Maximum aeroplane all-up mass:

$$M_{max} = 136\,000 \text{ kg.}$$

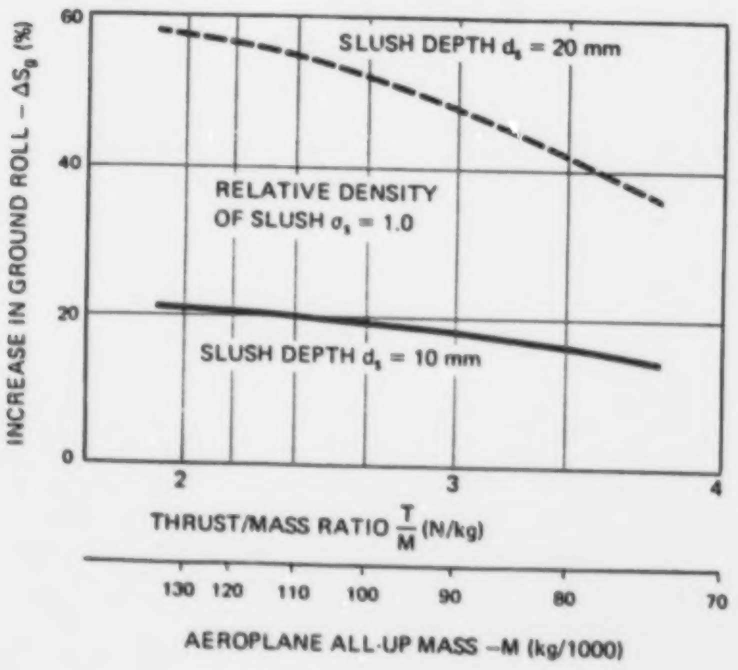

Figure B2. Effect of thrust/drag ratio on ground roll increment

11. Ground roll distances to lift-off have been estimated by step-by-step integration to be:

$$\Delta S_g = \sum_{0}^{V_{LOF}} \frac{M \Delta V^2}{2\,(T-D-D_S)}$$

12. The extent to which aeroplane take-off performance is modified by the presence of slush is a function of four major parameters:

a) the thrust/mass ratio of the aeroplane;

b) the aquapiloting speed of the tires in relation to the lift-off speed;

c) slush depth; and

d) slush density.

13. THRUST/MASS RATIO

Figure B2 illustrates that an increasing thrust/mass ratio, achieved in this example by reducing the aeroplane all-up mass, leads to a reduction in ground roll increment associated with a given slush condition. This effect is particularly marked at the greater slush depths where take-off performance is becoming marginal.

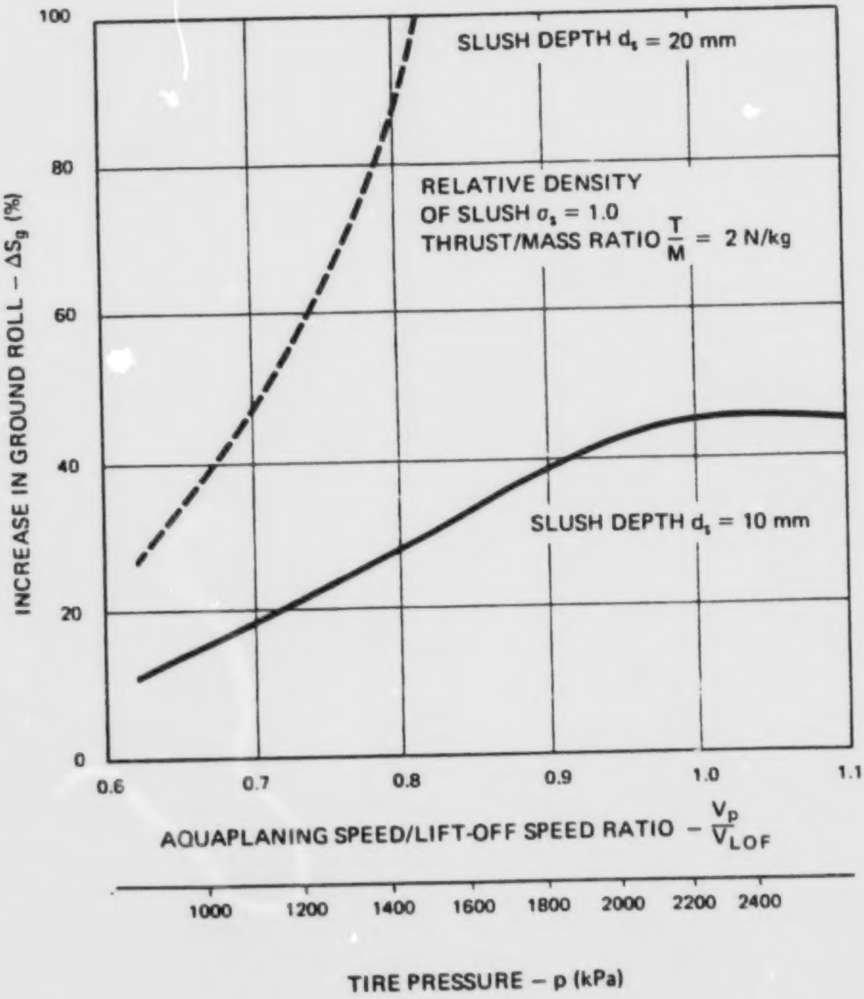

Figure B3. Effect of aquaplaning speed on ground roll increment

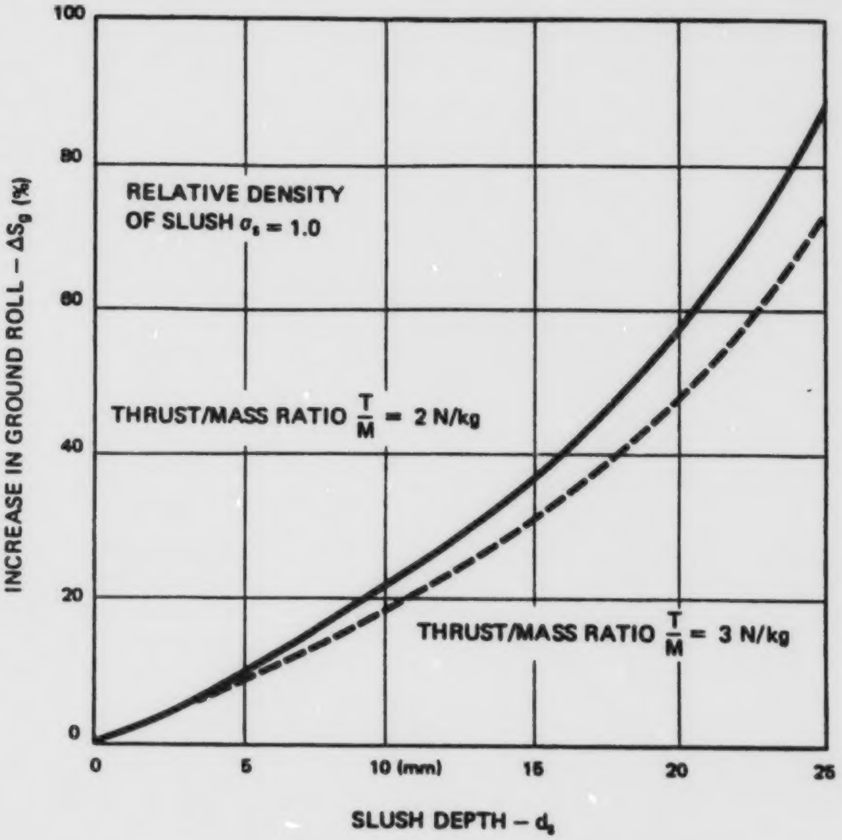

Figure B4. Effect of slush depth on ground roll increment

14. AQUAPLANING SPEED

Peak slush drag occurs at or near aquaplaning speed and any displacement of this peak towards higher speeds and hence to areas of lower excess thrust has an adverse effect on the performance penalty associated with a given slush condition. Figure B3 illustrates the marked rise in ground roll increment resulting from a displacement of aquaplaning speed towards lift-off speed. It is evident that relatively high tire pressures and hence aquaplaning speeds severely curtail an aeroplane's ability to operate satisfactorily in significant quantities of slush.

15. SLUSH DEPTH

Figure B4 illustrates the high sensitivity of ground roll performance to slush depth which occurs at significant slush depths. Even if sufficient runway is available to permit a particular operation with a 60 per cent ground roll increment, a sensitivity of 5 per cent distance per 1 mm depth poses severe measurement problems.

16. SLUSH DENSITY

16.1 Figure B5 a) shows that the ground roll increment associated with a particular slush depth is relatively insensitive to slush density over the usual range encountered in operation. It is important to note that the greatest performance penalty is not in fact associated with the highest value of slush density.

16.2 If the measure of slush depth is "water equivalent depth" any reduction in slush density is accompanied by an increase in actual depth. The sharp rise in performance penalty as slush density reduces from 1.0 to 0.6 is due to a progressive delay in the onset of aquaplaning and the achievement of higher and higher peak drags. (See Figure B1 a).) No further penalty occurs at slush densities below those for which $V_P = V_{LOF}$ ($\sigma_s = 0.54$ in this example).

16.3 The examples of the variation of performance penalty with thrust/mass ratio, aquaplaning speed, slush depth and density given in Figures B1 to B5 inclusive are felt to be not untypical of modern jet transport aeroplanes but it is not intended that the numerical results should be applicable to any particular aeroplane nor should it be assumed that some other parameter may not be significant in particular cases.

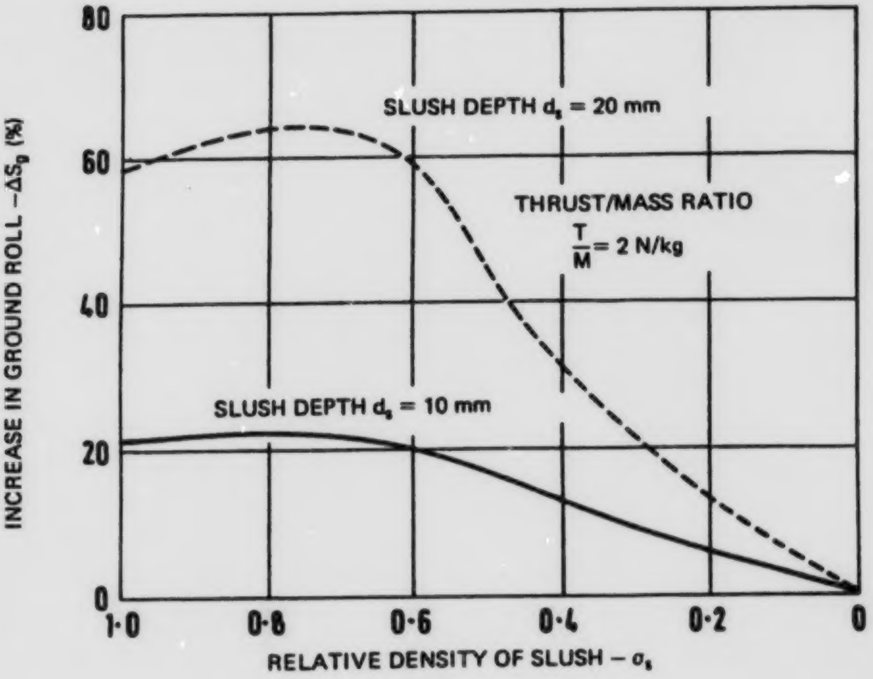

Figure B5 a) Effect of slush density on ground roll increment

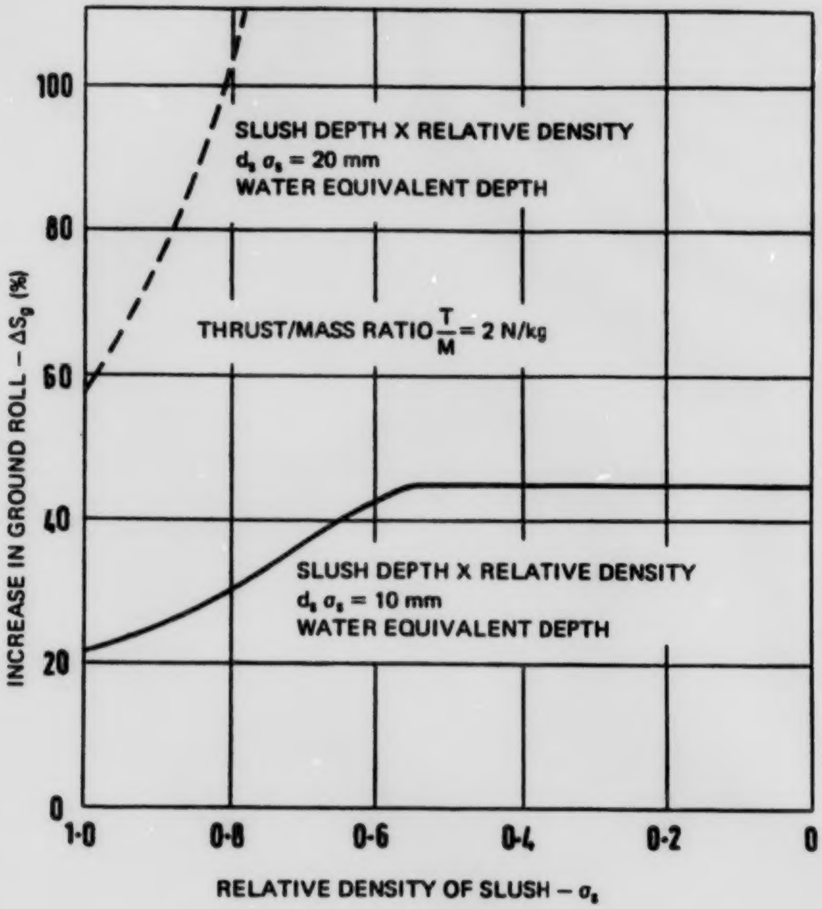

Figure B5 b) Effect of slush density on ground roll increment

REFERENCES

The following reports have been selected from the wide bibliography on slush as illustrating particular aspects of the slush drag problem:

1. Horne, Walter B.; Joyner, Upshur T.; Leland, Trafford J.W.: Studies of the Retardation Force Developed on an Aircraft Tire Rolling in Slush or Water. NASA TN D-552, 1960.

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3. Horne, Walter B.; Leland, Trafford J.W.: Prediction of Slush Drag on Aircraft Performance. FAA & NASA Joint Technical Conference on Slush Drag and Braking Problems, 1961.

4. Howell, Wayne D.; Sommers, Daniel E.: Slush Spray Patterns and Slush Damage. FAA & NASA Joint Technical Conference on Slush Drag and Braking Problems, 1961.

5. Horne, Walter B.; Dreher, Robert C.: Phenomena of Pneumatic Tire Hydroplaning. NASA TN D-2056, 1963.

6. Maltby, R.L.; Slatter, N.V.; Illingworth, J.K.B.: Some Measurements of the Drag due to Slush on an Ambassador Aircraft. R.A.E. Tech. Note. Aero. 2968, 1964.

7. Klueg, Eugene P.: Effect of Slush on Aircraft Drag and Wheel Rotation. FAA & NASA Joint Technical Conference on Slush Drag and Braking Problems, 1961.

Appendix C

Methods of Measuring Aeroplane Behaviour in Slush

1. The primary function of slush testing is to assess slush drag, impingement damage and powerplant ingestion characteristics of aeroplanes.

2. The apparatus and techniques employed by R.A.E. (Reference 1) in their investigations on the Ambassador and other aeroplanes are well documented and some experience has been gained by a number of manufacturers during prototype testing, covering both slush drag and ingestion problems. This experience has allowed a broad specification of desirable but not necessarily essential facilities and procedures to be drawn up as follows.

3. TEST FACILITY

3.1 Although satisfactory results have been obtained using troughs of only 45 m length, increasing aeroplane take-off speeds and the need to ensure a stabilized spray pattern suggest that a minimum trough length of 90 m should be provided.

3.2 In order to minimize the effort required to conduct routine trials, the ideal procedure would be to set up a permanent facility to accommodate current aeroplane types on a runway not less than 3 000 m long with the slush ponds not less than 1 200 m from either end. A runway width of 90 m is desirable with the slush ponds positioned to one side of the runway to leave sufficient unobstructed width for normal flying operations.

3.3 The bases of the troughs should be level to a fairly high degree of accuracy; ± 1.5 mm has been achieved using fine grain cement.

3.4 Ponds for main and nose wheels should be provided to allow the separate study of main and nose wheel effects. Ponds should be as wide as possible to minimize spray interference effects from the pond walls and to allow the maximum number of aeroplane types to use the facility.

Note.— The containment of the water or slush by flexible rubber walls of inverted 'T" section bonded to the levelled runway surface is satisfactory. Additional cross "dams" are necessary to minimize variations in water depth due to wind.

4. TEST MEDIA

4.1 Water allows the easiest handling and valuable testing can be carried out using this medium. Artificial slush manufactured from crushed ice, similar to that employed by NASA (Reference 2) has been used successfully although the manpower requirement is considerably greater than for water. Ambient temperatures of around 10°C have proved most satisfactory. Higher temperatures result in too rapid melting and lower, non-freezing temperatures result in non-uniform consistency during melting.

4.2 Investigations are in hand on the use of snow-making machines to provide artificial slush. This should provide a medium of more uniform consistency but results are not yet available.

5. INSTRUMENTATION

5.1 The most satisfactory method of arriving at the drag force on the aeroplane during its passage through water or artificial slush is that first employed by NASA, namely, to compare the aeroplane longitudinal acceleration before and after passing, with that during passage, through the trough. The parameters which must be recorded are aeroplane ground speed, pitch attitude and longitudinal acceleration. Measurements of pitch attitude are necessary to allow correction of longitudinal acceleration for changes in pitch attitude as the aeroplane enters and leaves the troughs. The most effective means of measuring aeroplane speed is by kine-theodolite. Longitudinal acceleration and pitch attitude are best measured by internal recording instrumentation.

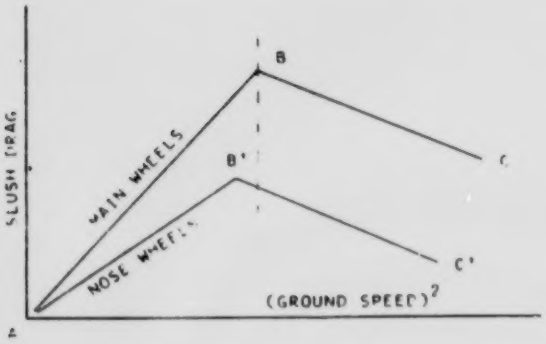
5.2 To allow a study of spray patterns, fairly generous cine-camera coverage is required. Records from the side, front and overhead have been found desirable to build up a full understanding of the spray pattern. Cameras mounted on the aeroplane have been proved less useful to date because of the view being obscured by spray. A polaroid plate camera arranged to provide three-quarter front views of the aeroplane passing through the trough has been used to provide valuable information to the test controller with the minimum of delay.

5.3 Continuous internal records of all relevant parameters associated with power plant and other vulnerable systems are desirable for ingestion tests.

6. TEST TECHNIQUE

6.1 Drag

NASA and R.A.E. work has suggested that, for a given aeroplane configuration and slush condition, the drag due to slush may be closely represented as follows:



Thus the establishment of the lines AB (AB') and BC (B'C') by a series of test measurements over a range of speeds provides basic data on the slush drag versus speed relationship below and above aquaplaning speed and closely fixes the aquaplaning speed itself. Tests in a range of slush depths and densities are necessary to establish the relationship between these parameters and slush drag and aquaplaning speed.

6.2 Ingestion

6.2.1 Tests to study ingestion and drag effects are sometimes carried out separately since the optimum techniques for the two types of test may differ.

6.2.2 To ensure that an aeroplane is free from ingestion problems or alternatively to establish the conditions in which ingestion becomes unacceptable, it is frequently necessary for the aeroplane to pass through a selection of slush conditions at a range of speeds up to the maximum to be used operationally, unless a marked change in spray pattern associated with the onset of aquaplaning makes further testing unnecessary.

6.2.3 Ingestion problems are more usually associated with spray from the nose wheel than from the main wheels. Auxiliary air intakes and systems sited in undercarriage bays have posed ingestion problems during past testing.

6.3 Damage

An assessment of actual and potential structural damage due to spray impingement is usually possible during drag and ingestion tests.

REFERENCES

1. N.V. Slatter: R.A.E. A Testing Technique for the Effects on Aircraft of Water or Slush on Runways, Tech. Report No. 65175, 1965.

2. Charles M. Middlesworth; John F. Marcy; Daniel E. Sommers; Don W. Conley: Experimental Techniques. FAA & NASA Joint Technical Conference on Slush Drag and Braking Problems, 1961.

Appendix D

Aircraft Rolling Resistance in Loose, Dry Snow

1. Based on a theoretical analysis supported by tests, the following information is presented on rolling resistance in loose, dry snow. The information may be used in estimating aircraft performance under such conditions.

2. The rolling resistance is primarily caused by compression of the snow, coefficient f_c, and by the dynamic effect, coefficient f_d, when the wheel forces the snow particles to move from their place in the snow layer to the surface below the tire.

3. Figure D1 presents a chart from which the snow dependent rolling resistance factor, f_s, can be read for various speeds and with snow depth, wheel load, snow density, tire radius and tire contact area width as parameters.

4. The wheel load, F_z, is the actual load on the wheel at the speed for which f_s is read. This means that one must take into account the reduction of F_z caused by wing lift as speed increases.

5. Rear wheels in a tandem arrangement will have a lower rolling resistance than the front wheels. As a conservative value 25 per cent of the front wheel resistance may be used.

6. The curves in Figure D1 are based on vertical load F_z = 100 000 N, snow density = 100 kg/m³, tire radius R = 55 cm and width of tire contact area b_k = 30 cm. It should be noted that accuracy of the f_s-value read in the chart will decrease as actual value of variables departs further from the reference value.

7. An example of the use of Figure D1 is shown in the figure.

8. The chart is based on the following formulae for f_c and f_d (SI units).

$$f_c = \frac{\sigma_i}{\varrho_i\sqrt{b}} \cdot \frac{b_k\varrho_o h_o}{F_z}\left[\frac{\sqrt{\pi}}{2} - \sqrt{b}\,(a-1) + \frac{b^{3/2}}{3}(a-1)^3\right]$$

$$f_d = \frac{b_k}{R} \cdot \frac{V^2\varrho_o h_o^2}{F_z}\left[1 - a\frac{\varrho_o}{\varrho_i} + \left(a\frac{\varrho_o}{\varrho_i} - \frac{\ell^2}{8Rh_o}\right)\ln\left(a\frac{\varrho}{\varrho_i}\right)\right]$$

Rolling resistance factor $f_s = f_c + f_d$

where:

F_z = Vertical wheel load in newtons

f_s = Snow dependent rolling resistance coefficient

f_c = Snow dependent rolling resistance coefficient due to compression of the snow

f_d = Snow dependent rolling resistance coefficient due to dynamic effects

R = Tire radius in metres

b_k = Width of tire contact area in metres

b = Constant, a good approximation is 1.5

h_o = Snow depth in metres

ϱ_o = Snow density in kilograms per cubic metre

ϱ_i = Ice density (= 920 kg/m³)

σ_i = Ice compressive strength (= 1 MN/m²)

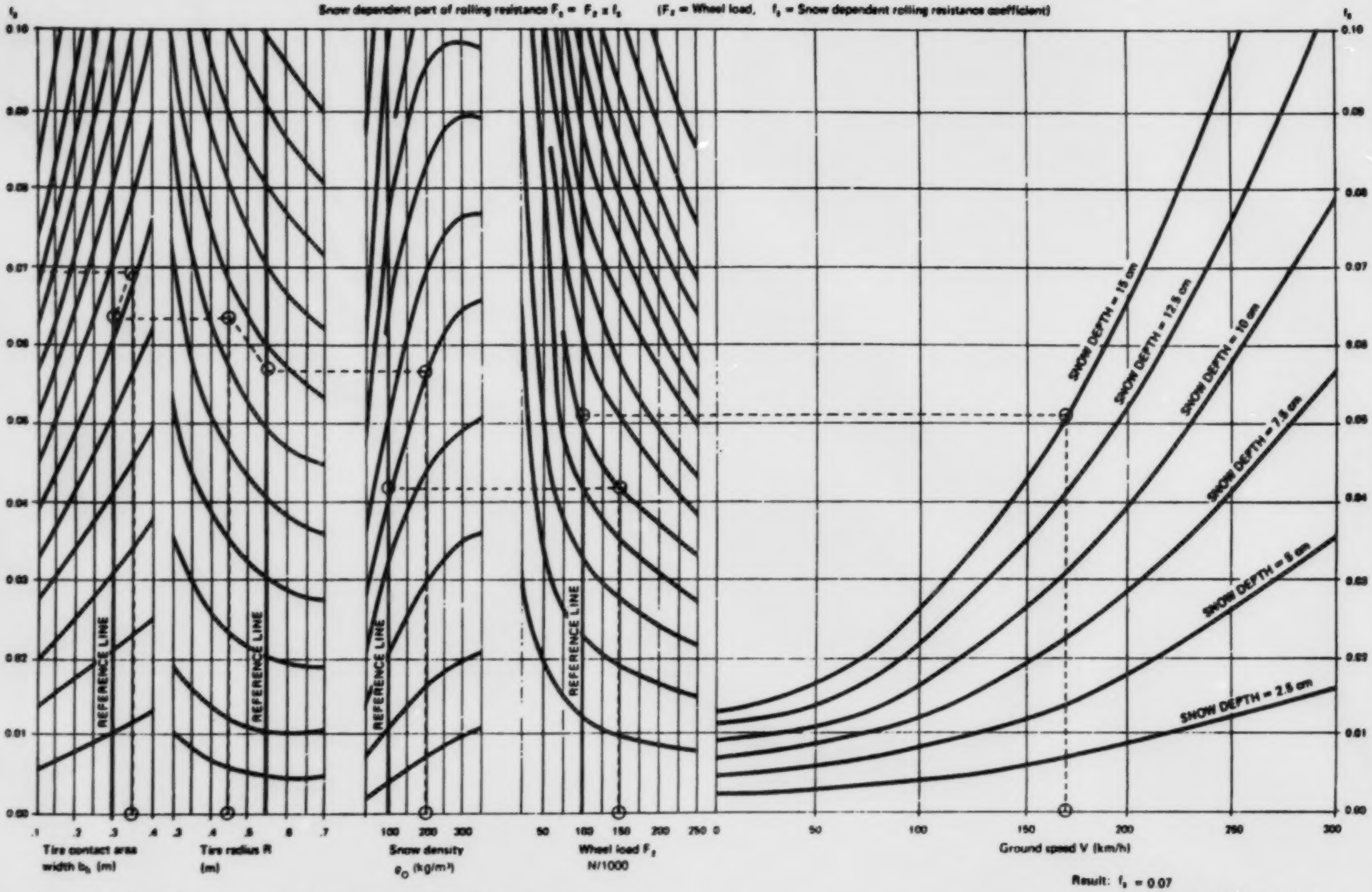
$\ell = 2\sqrt{R^2 - (0.85R)^2}$ in metres

$A = \ell\, b_k$ in square metres

$a = 1 + \sqrt{\frac{1}{b}\left(1 - \frac{F_z}{A\sigma_i}\right)};$

$a = 1$ for $\frac{F_z}{A\sigma_i}$ greater than 1

V = Aircraft speed in metres per second.



Snow dependent part of rolling resistance $F_s = F_z \times f_s$ (F_z = Wheel load, f_s = Snow dependent rolling resistance coefficient)

Example: Conditions: Snow depth h_0 = 15 cm Snow density ρ_0 = 200 kg/m³ Ground speed V = 170 km/h
Aircraft data: Wheel load F_z = 150 000 N Tire radius R = 0.45 m Tire contact area width b_0 = 0.35 m

Result: f_s = 0.07
F_s = 0.07 × 150 000 = 10 500 N
(× 0.25 if rear wheel
in tandem arrangement)

Figure D1. Rolling resistance in loose, dry snow

APPENDIX C

ADDITIONAL MATERIAL ON EFFECT OF RUNWAY CONTAMINATION ON AEROPLANE TAKE-OFF PERFORMANCE

C1 Displacement Drag

Equations for estimating the displacement drag are given in Section 4.2.1. Further evidence on the relationship between displacement drag and the contaminant are given below.

Figures C1 and C2 show the correlation between equation (2) and the tests results in slush and water, respectively. A tire drag coefficient of $C_D = 0.75$ is used for slush (Figure C1) and a $C_D = 0.70$ or 0.75 is used for water (Figure C2). Figure C3 shows the correlation between actual aeroplane test take-off distance and the predicted distance assuming that the rear wheels, which are in a bogie configuration, have zero displacement drag and no impingement drag.

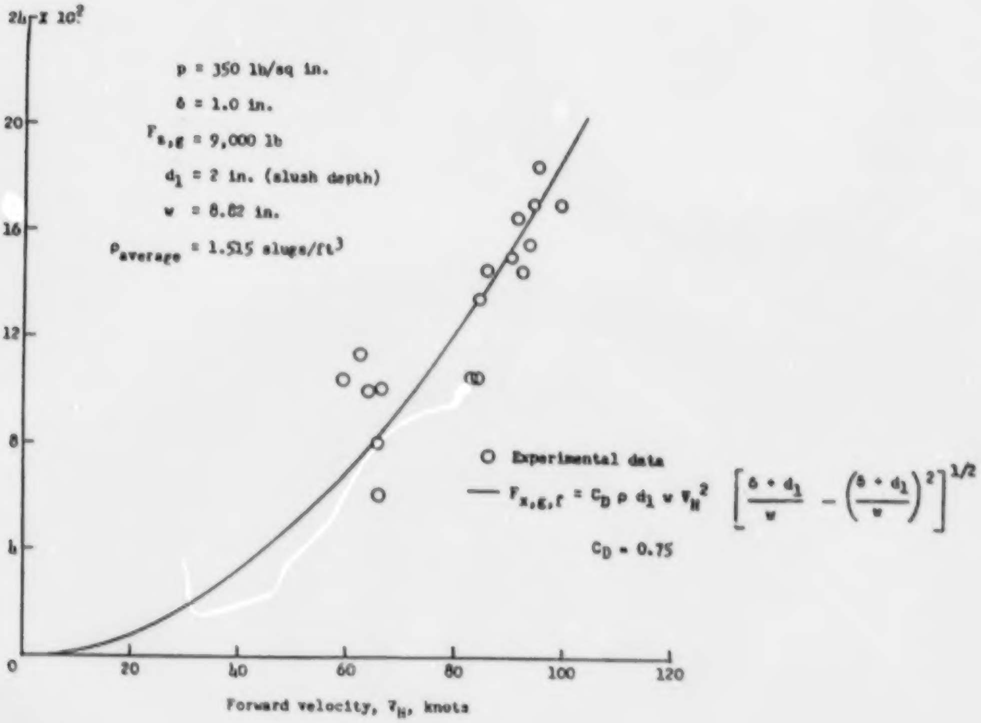


Figure C1 Variation of retardation force with forward velocity on slush covered runway

Source: Ref. 2, Figure 9

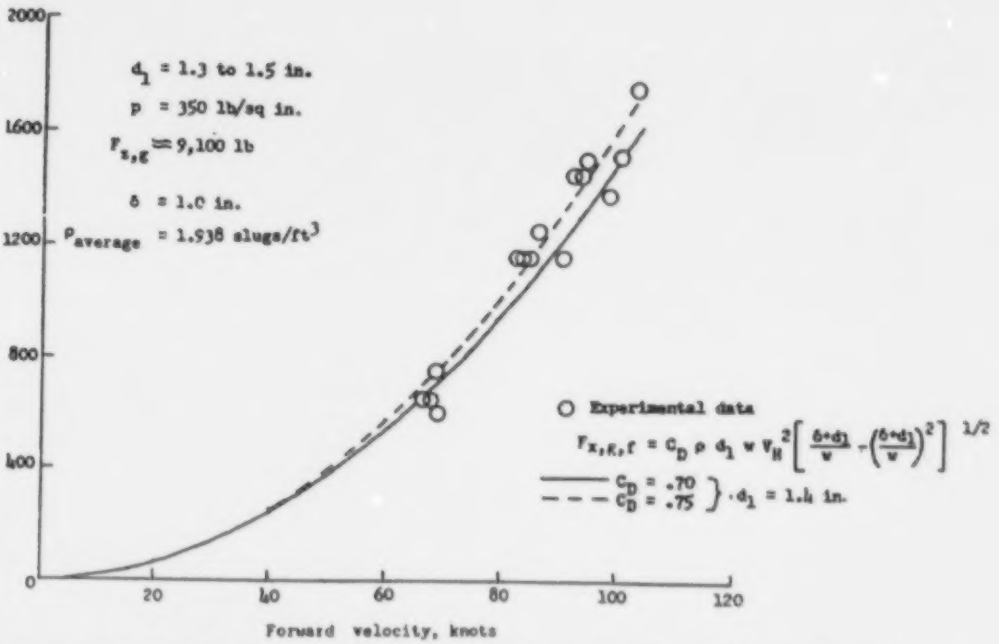


Figure C2 Variation of Retardation Force with Forward Velocity on Water Covered Runway

Source: Ref. 2, Figure 10

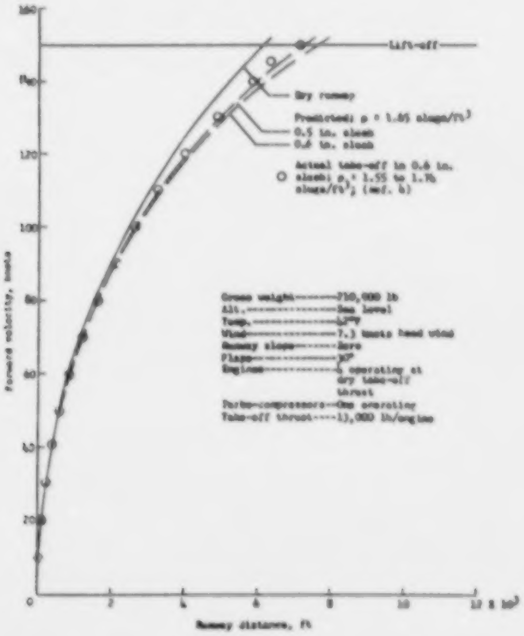


Figure C3 Comparison of the Calculated Take-off Distance with the Actual Take-off Distance Required for a Four-engine Jet Transport on a Runway Covered with 0.6 inch of Slush

Source: Ref. 2, Figure 13

Figure C4 shows that the rear bogie wheels are in fact under some influence by the contaminate even through it might be only of small order.

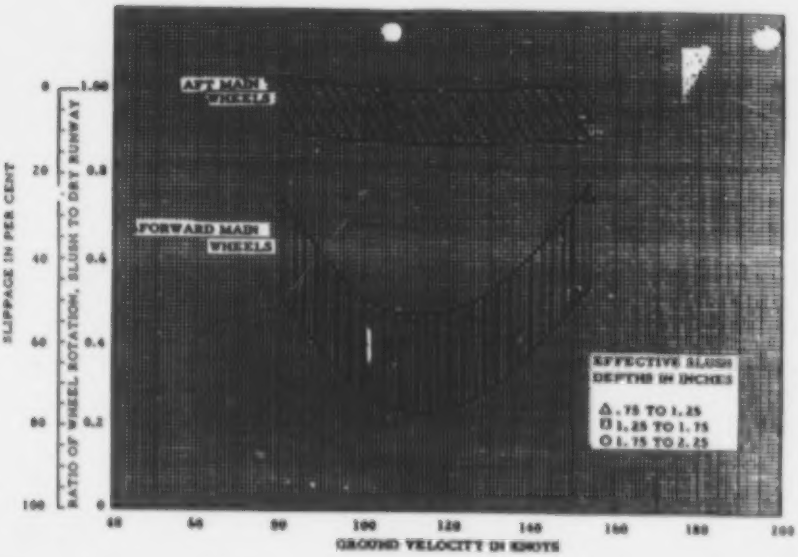


Figure C4 Effect of slush on main wheel rotation

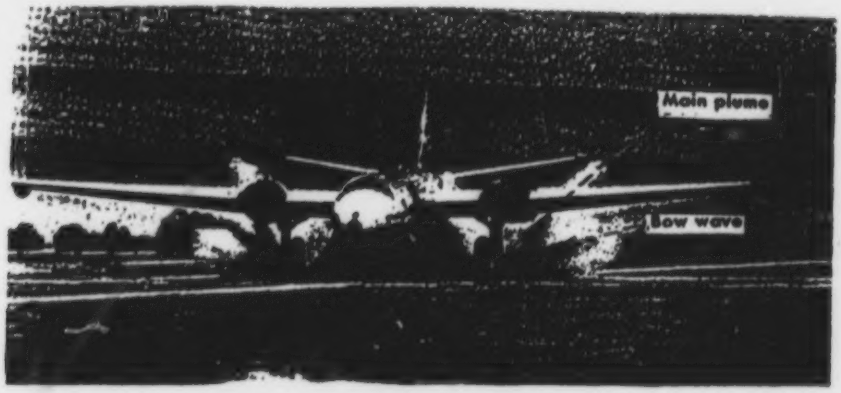
Source: Ref. 3, Figure 42, Page 71

C2. Impingement Drag

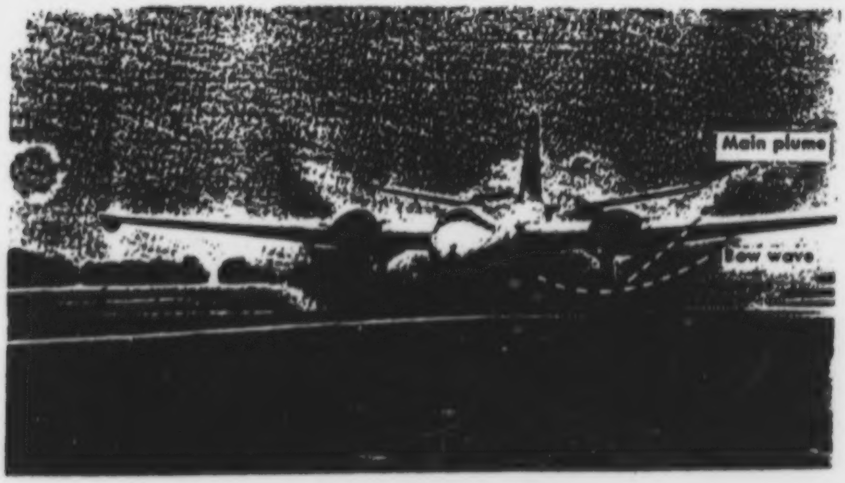
Spray patterns and the resulting impingement drag are described in Section 4.2.2. Further material on the spray patterns drawn from several references is presented below.

Spray patterns for the Convair 880 in slush, Figure 4.3, showed that the lateral displacement of the contaminant was more pronounced at the lower speeds, becoming extremely narrow at 155 knots. The vertical pattern was maximum at 110-120 knots and contributed to the increase in impingement drag up to these speeds; this pattern accounts in part for the trend in the drag curves. The slush spray generated by the nose wheel increased as the slush depth was increased. Slush displaced between the forward main wheels was moved in a vertical direction to form a "rooster tail" and the "rooster tail" formed by the nose wheels was impinged on the main wheels and the entire length of the fuselage lower surface. Very little of the main wheel spray impinged on the wing or wing flaps.

Spray patterns and angles were measured and reported in Ref. 8, for several different aeroplane types and the report concludes that the bow wave immediately in front of the tyre rise as high as 2½ times the wheel diameter at low speeds, passing on either side of the wheel and rising to about 30° at low speeds and decreasing to 15° at high speeds. The main plume formed from the spray projected upwards and outwards from the side of tyre ground contact area account for most of the displaced water which rises at an angle of 20° to the horizontal and at an angle of 40° to 50° sideways. The tests also showed that the longitudinal and lateral spray patterns are essentially independent of the aeroplanes speed. Figure 4.4 and Figures C5, C6, C7 and C8 illustrates the above.



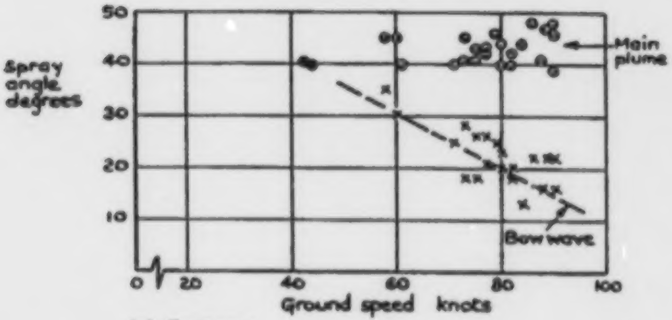
(a) Bow wave and main plume at $V/\sqrt{P} \doteq 9$



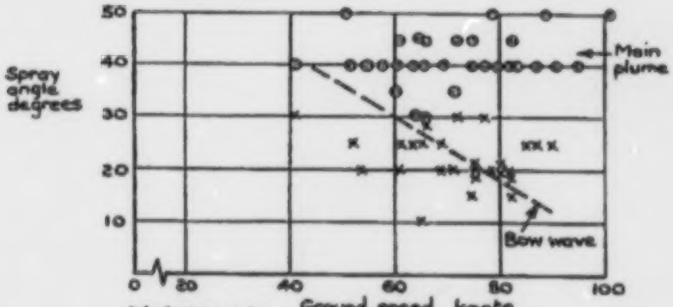
(b) Main plume at $V/\sqrt{P} \doteq 7$

Figure C5 Characteristic Spray Pattern for Canberra At and Before Aquaplaning Speed

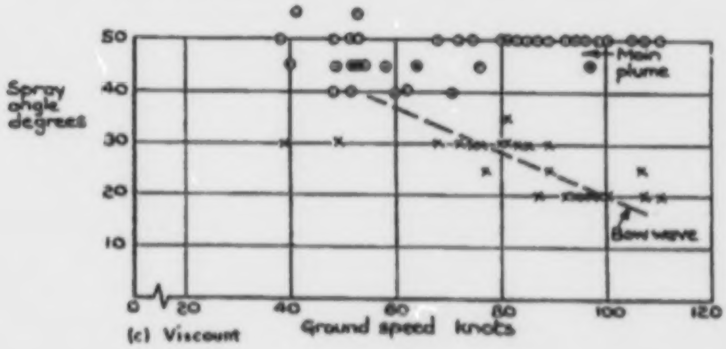
Source: Ref. 8, Figure 20, Page 63



(a) Canberra



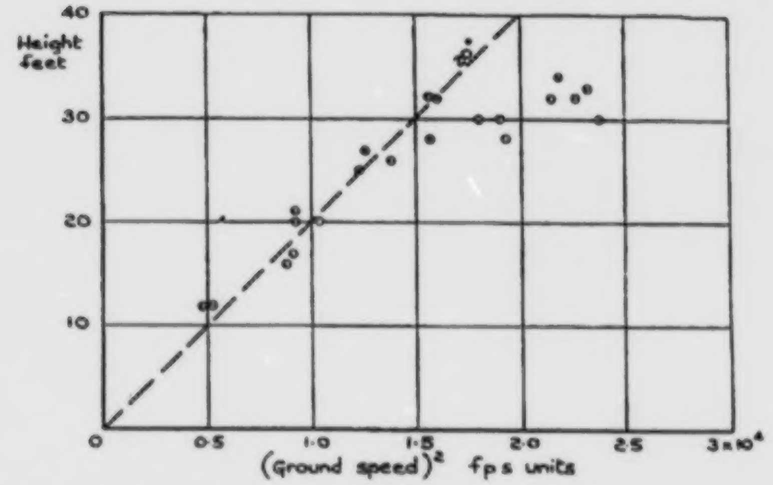
(b) Ambassador



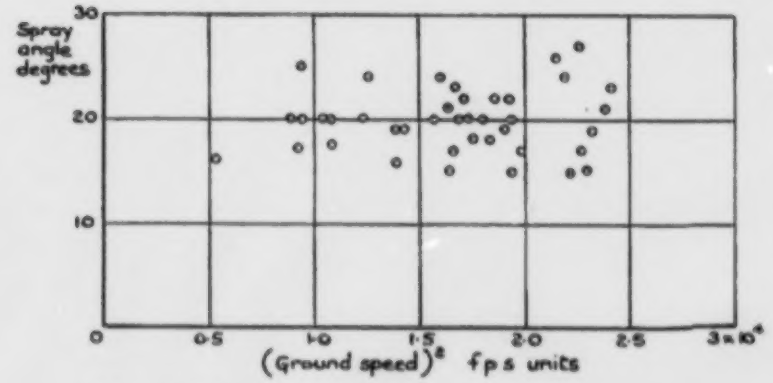
(c) Viscount

Figure C6 Development of Spray Plumes in Front Elevation

Source: Ref. 8, Figure 25, Page 68



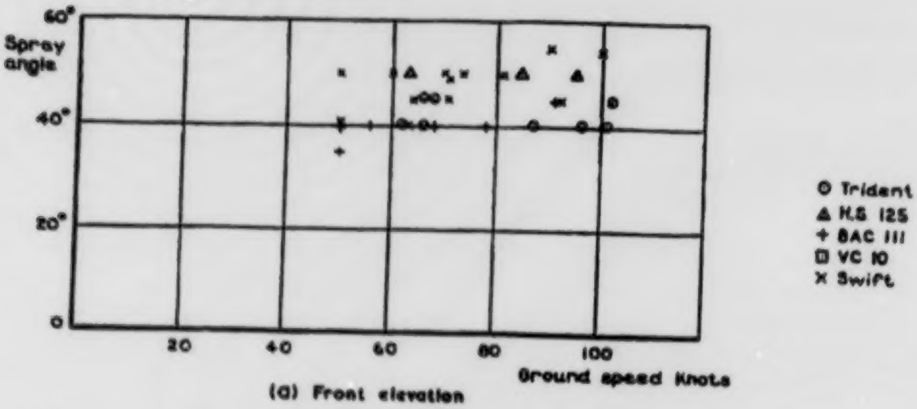
(a) Maximum height reached by spray



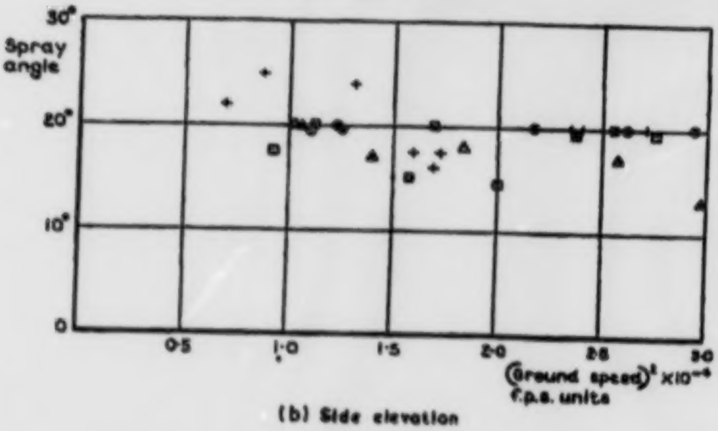
(b) Angular development of spray

Figure C7 Development of Main Spray Plume in Side Elevation for Canberra Aeroplane

Source: Ref. 3, Figure 26, Page 68



(a) Front elevation



(b) Side elevation

Figure C8 Spray angles for Trident, Hawker Siddley 125, BAC 111, Viscount 10 and Swift Aeroplanes

Source: Ref. 8, Figure 29, Page 70

Tests carried out on the BAC 111 aeroplane, Ref. 18b, shows that at the lower speeds, there was considerable impingement on the flaps and rear fuselage from the main wheels as well as a strong bow wave. At aquaplaning speeds the amount of impingement from the main wheels was negligible. The nose wheel spray did not decrease as speed increased and the highest pattern occurred just before the aquaplaning speed.

C3 Total Contaminant Drag Coefficient

Total contaminant drag is described in Section 4.2.3. Further evidence on the relationship between the drag coefficient and speed is given below.

Figures 4.1 and C9 demonstrates that, for the Convair 800 aeroplane, the total contaminated drag coefficient C_{Ds} is essentially constant at all speeds up to the point at which aquaplaning occurs and then reduces linearly thereafter. Figures C10, C11, C12 and C13 demonstrates this for the Airspeed Ambassador, Vickers Viscount and English Electric Canberra aeroplanes including the effects of C_L and, Figure C14 demonstrates it for the BAC 111 aeroplane.

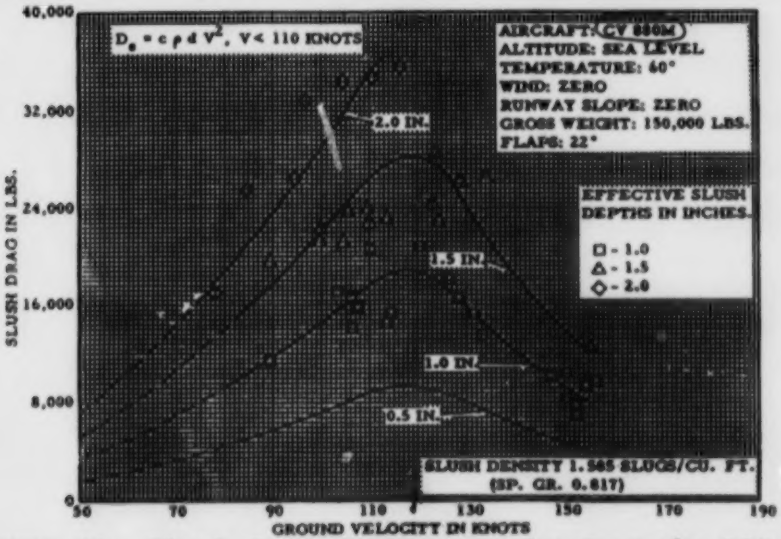


Figure C9 Slush Drag Forces on the Convair 880 Aircraft

Source: Ref. 3, Figure 45, Page 80

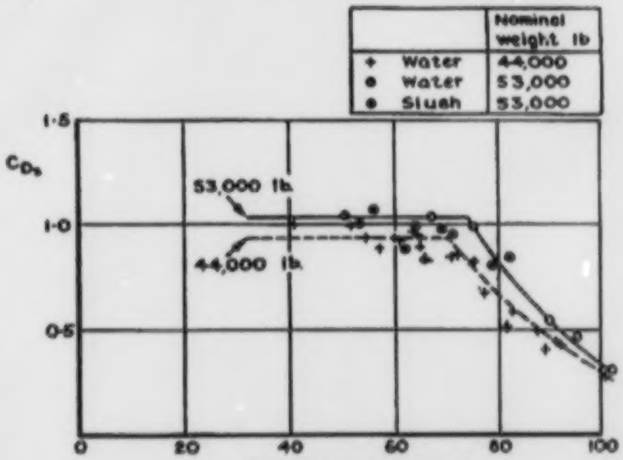
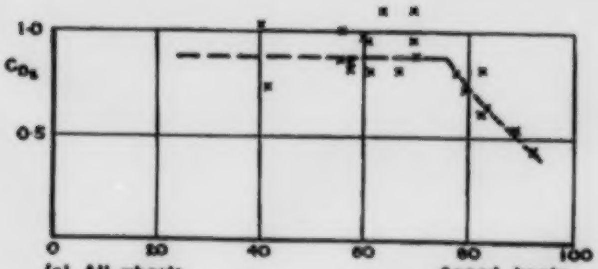
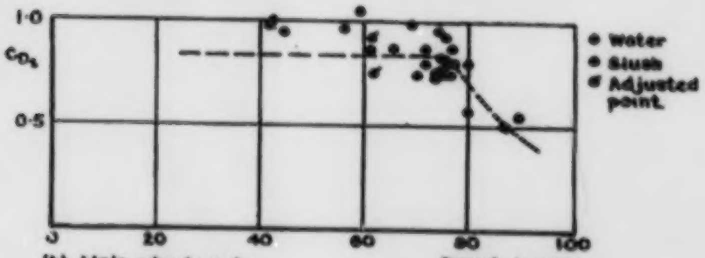


Figure C10 Variation of Slush Drag Coefficient with Speed - All Wheels, for Ambassador Aeroplane

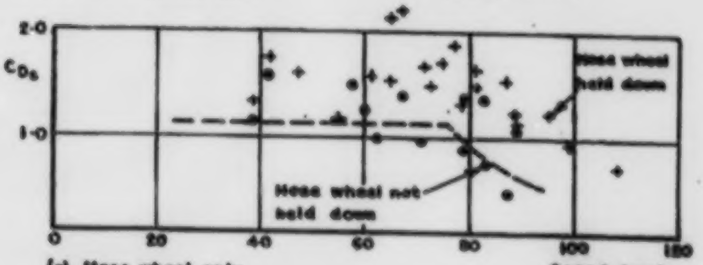
Source: Ref. 8, Figure 12, Page 58



(a) All wheels



(b) Main wheels only.

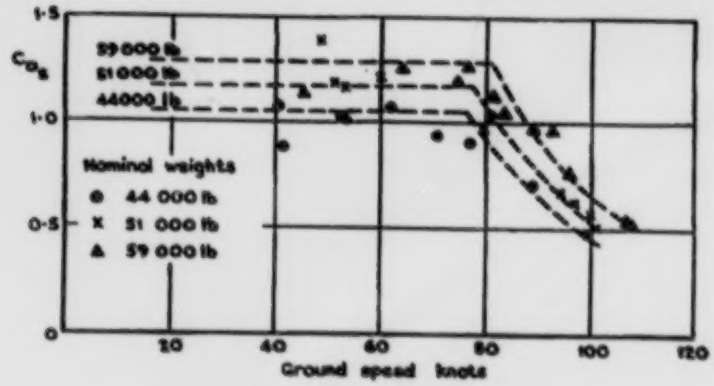


(c) Nose wheel only.

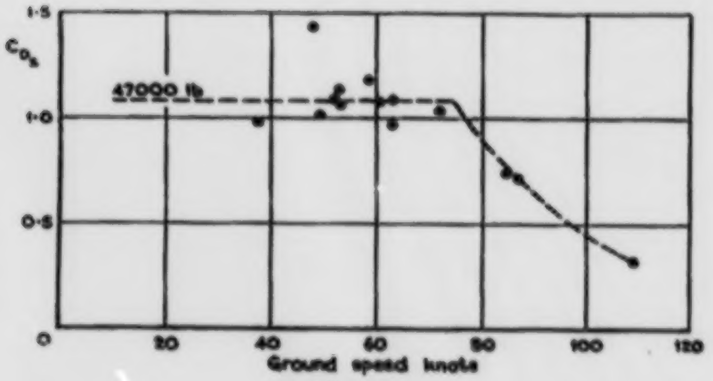
Figure C11 Variation of Slush Drag Coefficient With Speed for Canberra Aeroplane

Source: Ref. 8, Figure 11, Page 58

Note The individual points are calculated for the appropriate tyre widths. The lines are derived from Fig. 10 & 11 and a mean total tyre width of 3·9 ft. in Fig.(a) & 5 ft in Fig.(b)



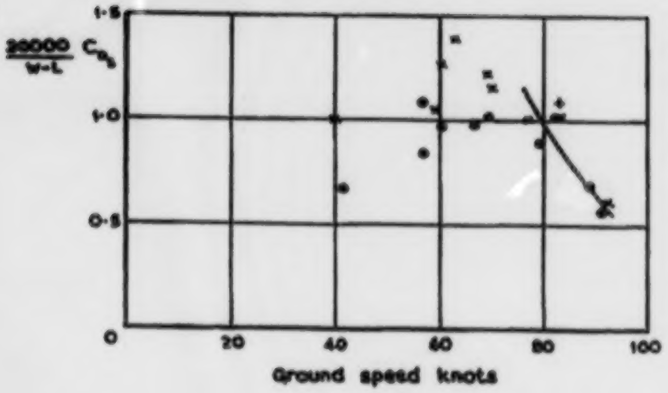
(a) Main wheels only



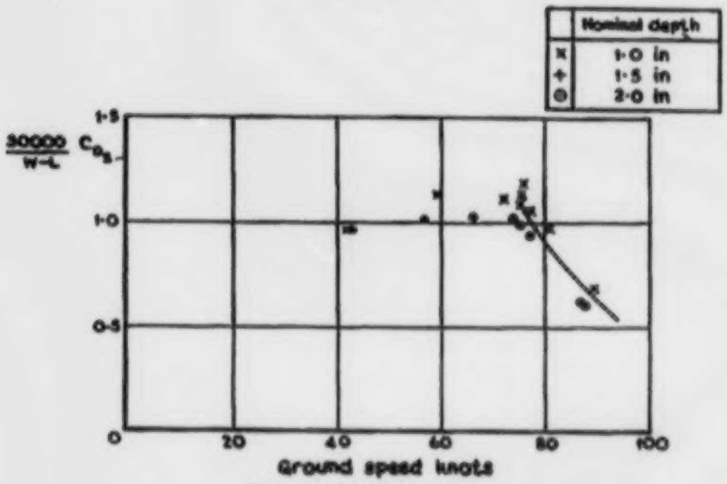
(b) All wheels

Figure C12 Variation of Slush Drag Coefficient With Speed for Viscount Aeroplane

Source: Ref. 8, Figure 13, Page 59



(a) All wheels



(b) Main wheels only

Figure C13 Variation of Slush Drag Coefficient Corrected to a Wheel Load of 30,000 lb for Canberra Aeroplane

Source: Ref. 8, Figure 14, Page 59

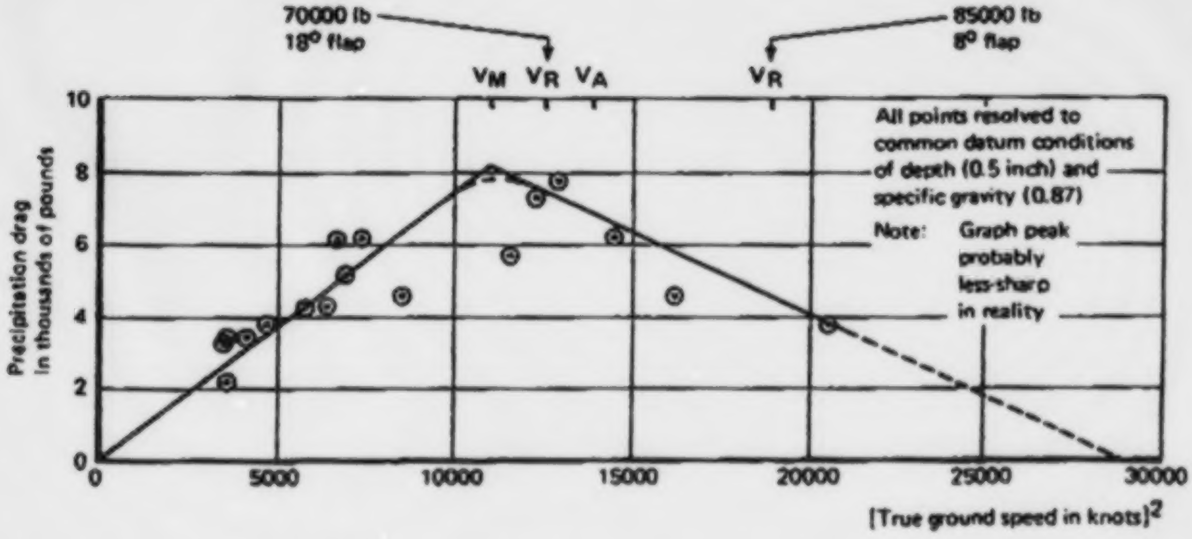


Figure C14 Variation of Slush Drag Coefficient (All Wheels in Slush or Water) With Speed for BAC 111 Aeroplane

Source: Ref. 18B, Figure 1

The type of scatter that can occur when trying to carry out appropriate tests to establish values of C_{Ds} are shown in Figures C15 and C16.

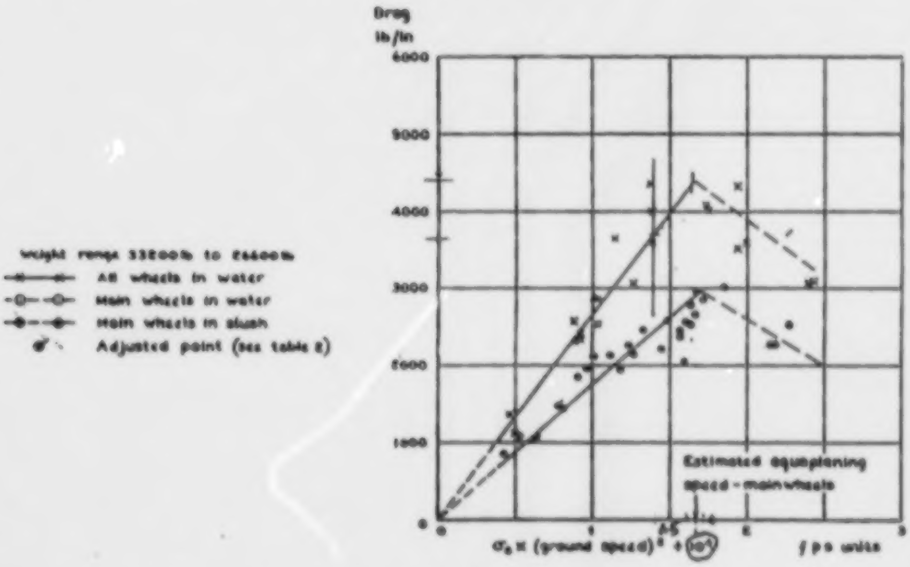


Figure C15 Variation of Drag Per Unit Depth With Equivalent Speed for Canberra Aeroplane

Source: Ref. 8, Figure 5, Page 55

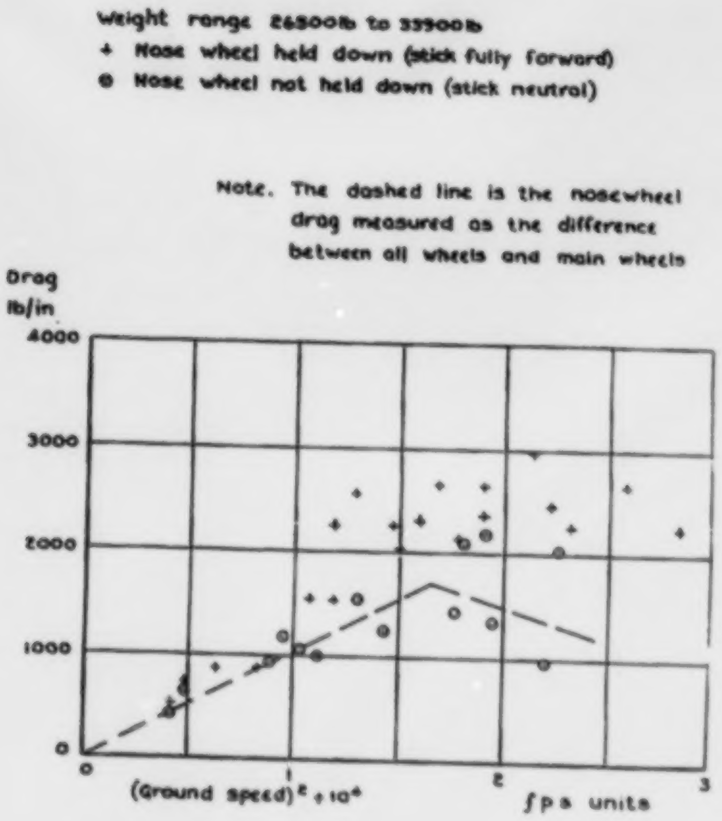


Figure C16 Variation of Nosewheel Drag With Speed in Water for Canberra Aeroplane

Source: Ref. 8, Figure 6, Page 55

APPENDIX D

BOEING 747 UTILS
SIMULATOR TRIAL RESULTS

AERCOL

Initial Simulator Trials Results

prepared by L.D. Reid

April 20, 1990

AERCOL Ref. 89-15

AEROSPACE ENGINEERING AND RESEARCH CONSULTANTS LIMITED
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Several series of trials were flown in the UTIAS B747 flight simulator with the motion-base off and a 40° field-of-view visual display. The test pilot was Mr. Al Baker. Measurements were made of accelerate-stop distance and distance to 35 feet under a range of conditions (a 10 kt headwind was always present). The conditions covered are contained in the enclosed flight test log sheets. They were selected by Mr. Ken Owen.

Each takeoff began on a patch of bare runway. The pilot ran up the engines to the takeoff setting before releasing the brakes. The EPR was then further adjusted once at an indicated airspeed of 60 kts. An audio warning chime was activated briefly upon reaching V_1 in the case of an accelerate-stop test or upon reaching V_R in the case of a takeoff test. The pilot attempted to achieve an airspeed of V_{35} at an altitude of 35 feet during takeoffs, where $V_{35} = 1.25\ V_s$. Except as indicated (one trial) all four engines were operating during the flight tests.

Computer printouts for all the test runs are enclosed (ignore the headwind and air temperature values). The runs with File Names AB0052, 61, 85 and 93 have been reprocessed to include an improved anti-skid brake model. This new model removes an uneven system response following hydroplaning present in the original system. Tables 1 and 2 contain processed data extracted from the raw printouts. The following definitions apply to these tables (accelerate-stop/takeoff):

COND. 1 - 530,000 lbs. aircraft weight; - 2°C air temperature; 500 ft. airport altitude.

COND. 2 - 530,000/-2/3,500

COND. 3 - 530,000/27/500

COND. 4 - 530,000/27/3,500

COND. 5 - 680,000/-2/500

COND. 6 - 680,000/-2/3,500

COND. 7 - 680,000/27/500

COND. 8 - 680,000/27/500

CASE D.6 - Dry; μ_{max} = 0.6

CASE D.3 - Dry; μ_{max} = 0.3

CASE D.2 - Dry; μ_{max} = 0.2

CASE W - 6 mm Water; μ_{max} = 0.3

CASE SL - 8 mm Slush; μ_{max} = 0.2

CASE SN - 20 mm Snow; μ_{max} = 0.2

CASE I - Ice; μ_{max} = 0.1

V_1 t/x - time/distance from brake release to reach V_1

V_R t/x - time/distance from brake release to reach V_R

END t/x - time/distance from brake release to either stop or pass through 35

The plots of acceleration versus time from brake release are enclosed. They are numbered according to the COND. code used in the tables. The dry case used is D.6.

The V_{MC_G} results are given in Table 3. These trials were carried out for COND. 5. The headwind was zero and the wind was a pure crosswind from the left making a right angle with the runway. The value of μ_{max} was adjusted as shown in the table. The pilot began by initiating a normal takeoff. At an indicated airspeed of 111 kts. the left hand outboard engine (No. 1) was failed. The pilot then attempted to keep the aircraft aligned with the runway by using rudder pedals only. If he felt that he could successfully keep the aircraft aligned and keep the lateral deviation below 25 - 30 ft. then he responded yes (Y), otherwise he responded no (N).

TABLE 1

TAKEOFF 530,000 lbs.

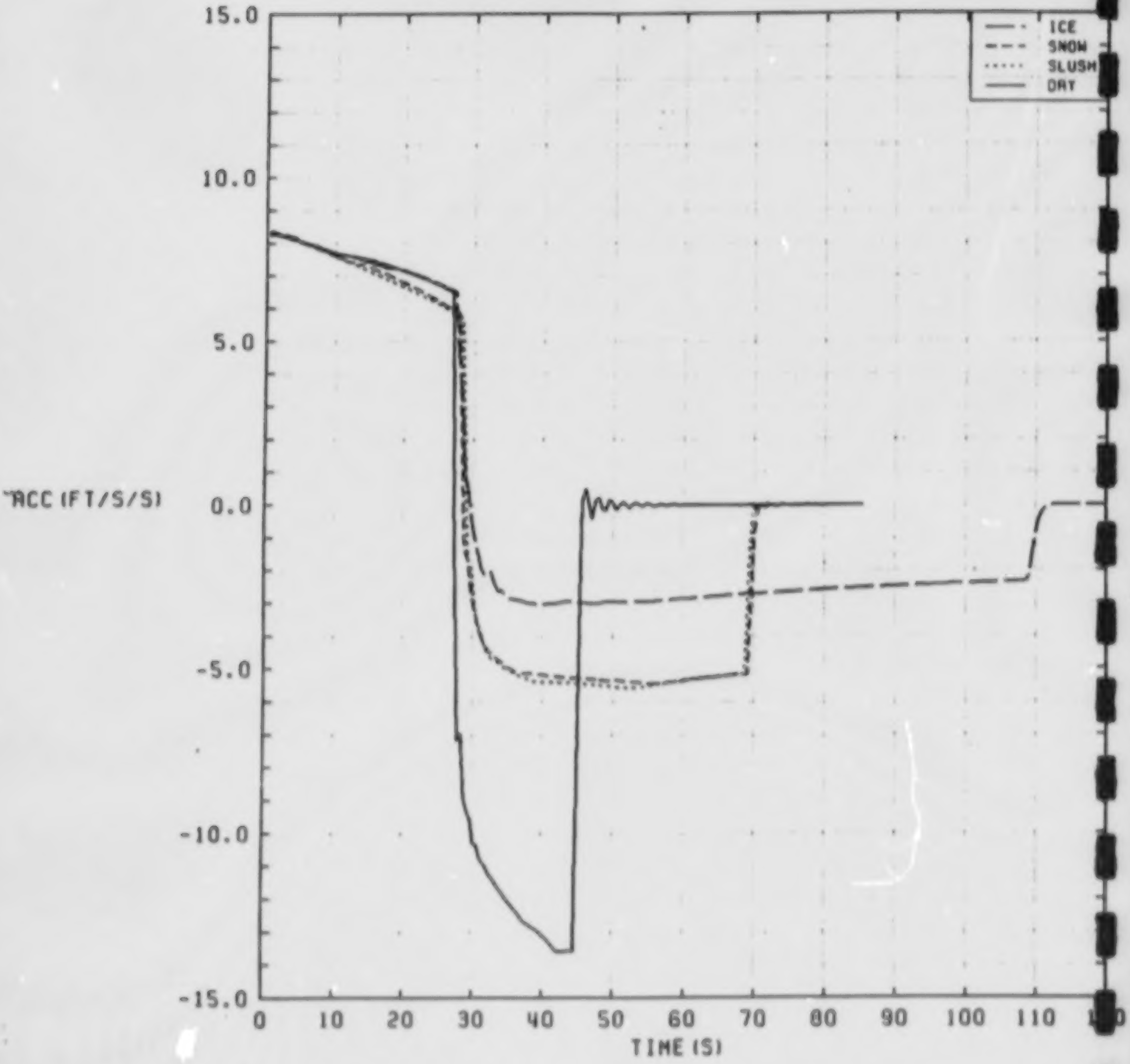
FILE	COND.	CASE	V_1 t s	V_R t s	END t s	V_1 x ft	V_R x ft	END x ft
AB0063	1	D.6	27.4	—	46.1	2,934	—	5,016
AB0064			26.9	29.3	35.5	2,876	3,385	4,799
AB0065	1	D.3	27.4	—	57.1	2,891	—	6,146
AB0066	1	D.2	27.4	—	70.2	2,921	—	7,521
AB0067			27.4	29.3	36.5	2,928	3,336	5,049
AB0068	1	SL	28.3	—	70.6	3,069	—	7,637
AB0069			28.3	30.7	38.4	3,100	3,609	5,490
AB0070	1	SN	27.8	—	71.0	3,020	—	7,726
AB0071			27.8	30.2	38.4	3,045	3,551	5,465
AB0074	1	I	26.9	—	112.3	2,863	—	11,728
AB 034	2	D.6	31.2	—	50.9	3,597	—	6,024
AB035			31.2	33.1	38.9	3,559	3,991	5,436
AB038	2	SL	32.2	—	77.8	3,816	—	9,148
AB039			32.6	34.6	41.3	3,849	4,281	5,980
AB040	2	SN	32.6	—	77.3	3,871	—	9,086
AB041			32.2	34.6	41.8	3,775	4,316	6,124
AB042	2	I	29.7	—	119.0	3,555	—	13,456
AB0075	3	D.6	33.1	—	51.4	3,570	—	5,596
AB0076			32.6	35.0	43.7	3,484	3,987	6,014
AB0077	3	W	34.6	—	72.5	3,751	—	8,023
AB0078			34.6	37.4	46.6	3,769	4,375	6,465
AB0043	4	D.6	36.0	—	56.2	4,156	—	6,679
AB0044			36.0	38.9	47.5	4,181	4,835	7,051
AB0045	4	W	37.9	—	78.7	4,520	—	9,581
AB0046			37.9	40.8	49.4	4,541	5,193	7,321
STA046	4	W	31.2	—	67.2	3,163	—	7,062
AB0048		ENG FAIL	31.7	46.1	56.2	3,191	6,247	8,760

TABLE 2
TAKEOFF 680,000 lbs.

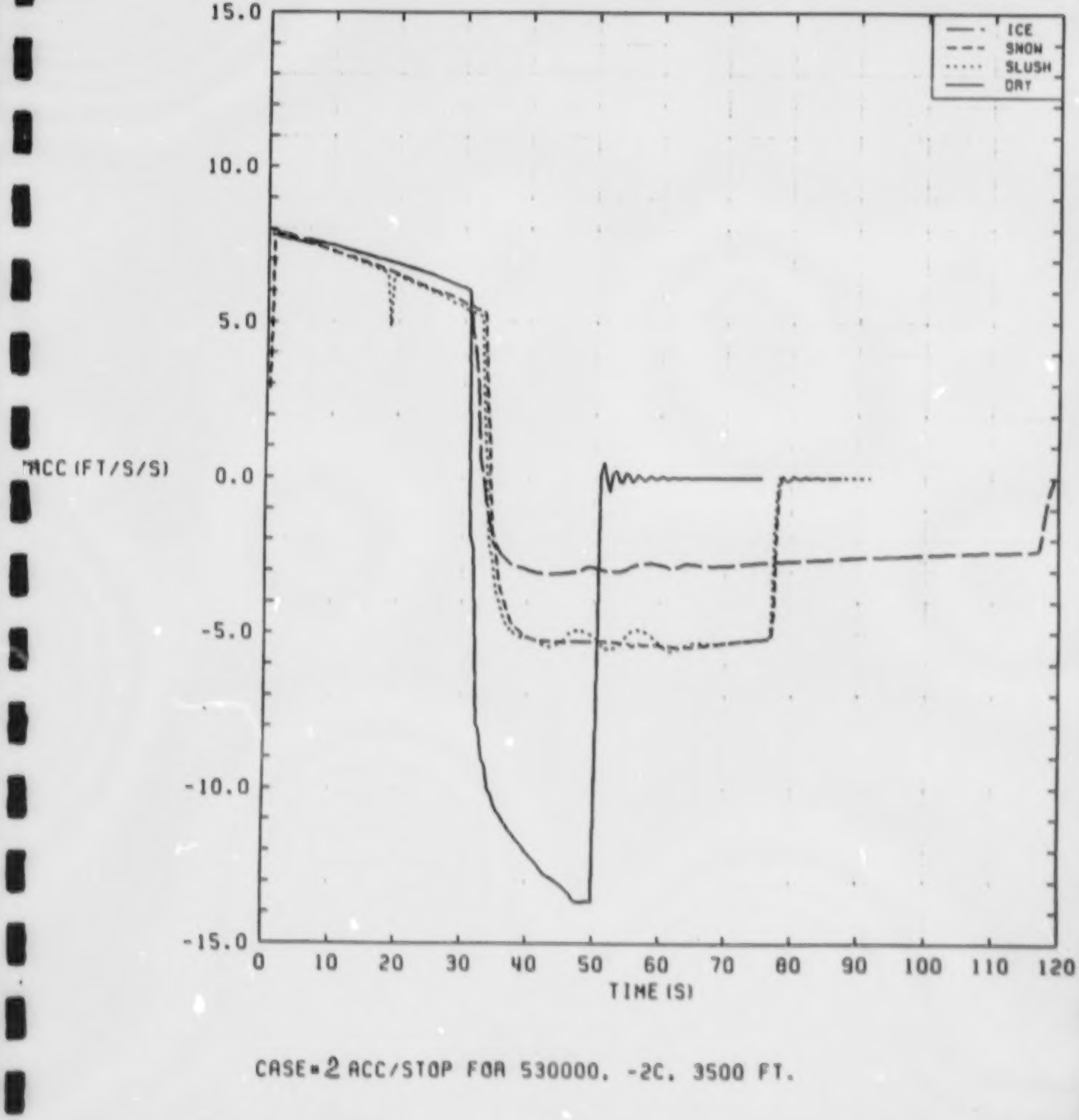
FILE	COND.	CASE	V_1 t s	V_R t s	END t s	V_1 x ft	V_R x ft	END x ft
AB0080	5	D.6	43.7	—	69.6	5,794	—	8,959
AB0081			44.2	46.6	53.3	5,833	6,448	8,311
AB0082	5	D.3	43.7	—	77.3	5,779	—	10,112
AB0083	5	D.2	44.2	—	93.1	5,849	—	12,144
AB0084			43.7	46.1	54.7	5,820	6,436	8,793
AB0085	5	SL	46.6	—	94.6	6,319	—	12,458
AB0086			46.6	49.9	58.1	6,344	7,204	9,541
AB0087	5	SN	46.6	—	95.5	6,307	—	12,454
AB0088			47.0	50.4	58.6	6,388	7,249	9,438
AB0089	5	I	43.7	—	138.2	5,736	—	17,340
AB0050	6	D.6	53.8	—	79.7	7,758	—	11,127
AB0051			52.8	55.7	64.3	7,455	8,240	10,769
AB0052	6	SL	57.6	—	118.6	8,489	—	18,087
AB0053			57.6	61.0	69.1	8,461	9,376	11,802
AB0055	6	SN	57.6	—	109.0	8,530	—	15,596
AB0056			58.1	61.9	70.1	8,604	9,650	12,049
AB0058	6	I	52.3	—	150.7	7,447	—	20,210
AB0091	7	D.6	48.5	—	74.9	6,562	—	9,814
AB0092			48.5	50.9	60.5	6,547	7,171	9,929
AB0093	7	W	52.3	—	121.0	7,248	—	19,225
AB0094			52.3	54.7	62.9	7,241	7,865	10,165
AB0059	8	D.6	60.0	—	86.9	8,619	—	12,247
AB0060			59.5	62.9	71.0	8,525	9,445	11,874
AB0061	8	W	63.4	—	142.6	9,308	—	24,061
AB0062			64.8	68.2	76.8	9,536	10,458	12,921

TABLE 3
V_{mc_G} TESTS

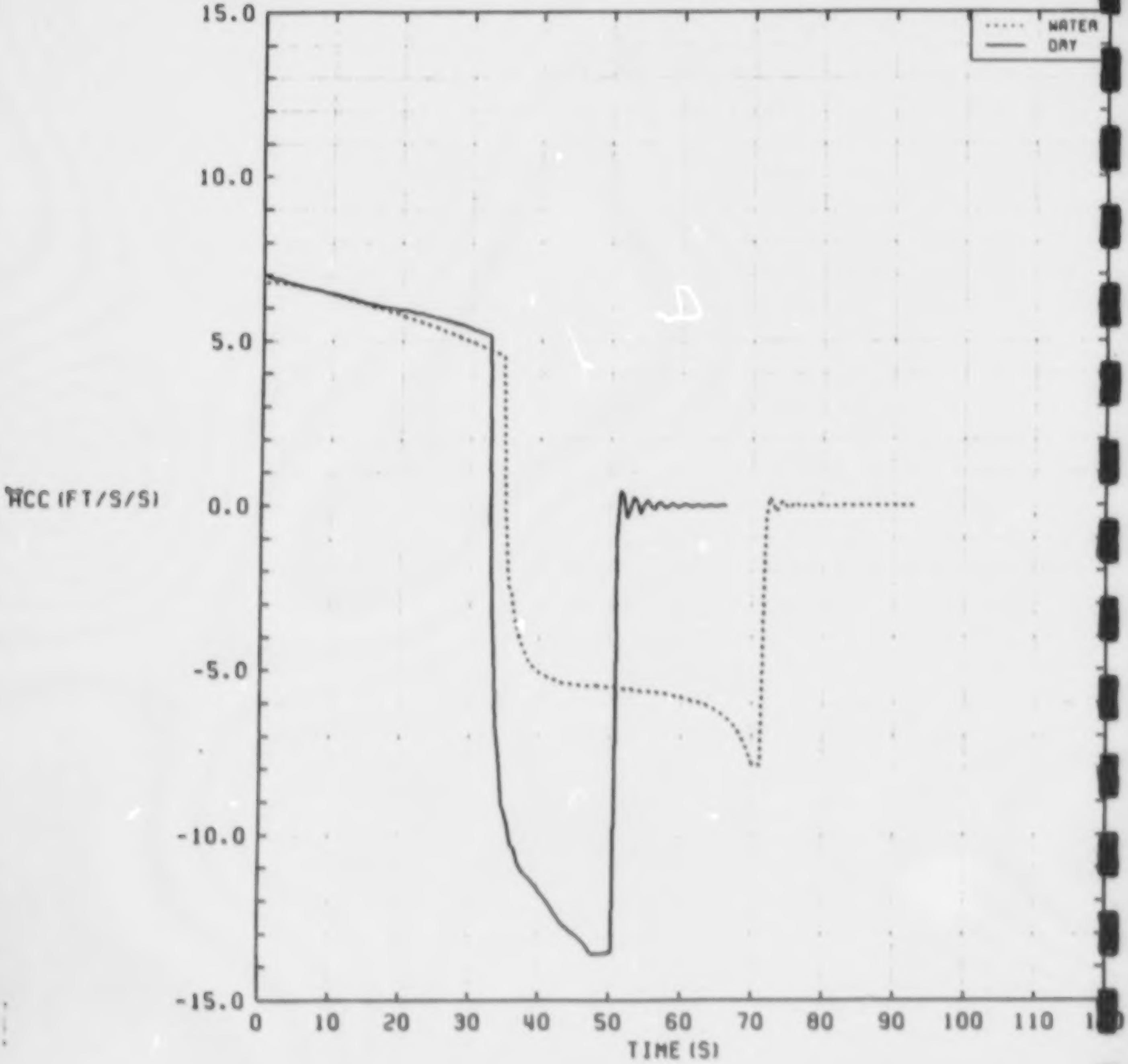
No.	WIND kts	μ_{MAX}	PILOT RESPONSE Y or N
1.	0	0.1	Y
2.	20	0.3	Y
3.	30	0.3	N
4.	25	0.3	N
5.	20	0.3	Y
6.	20	0.2	N
7.	15	0.2	N
8.	10	0.2	Y
9.	10	0.1	N
10.	5	0.1	Y
11.	35	0.6	Y



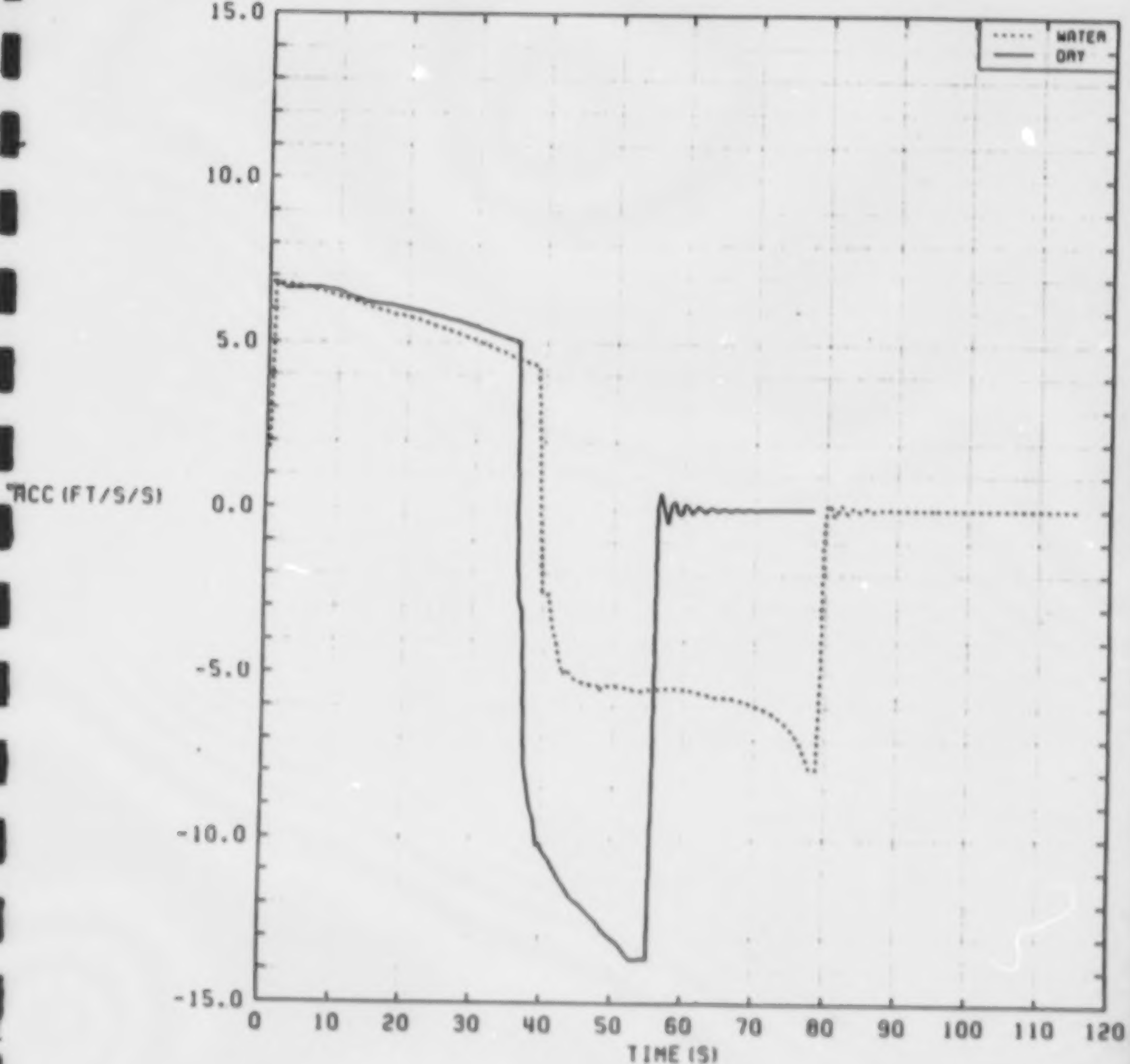
CASE=/ ACC/STOP FOR 530000, -2C, 500 FT.



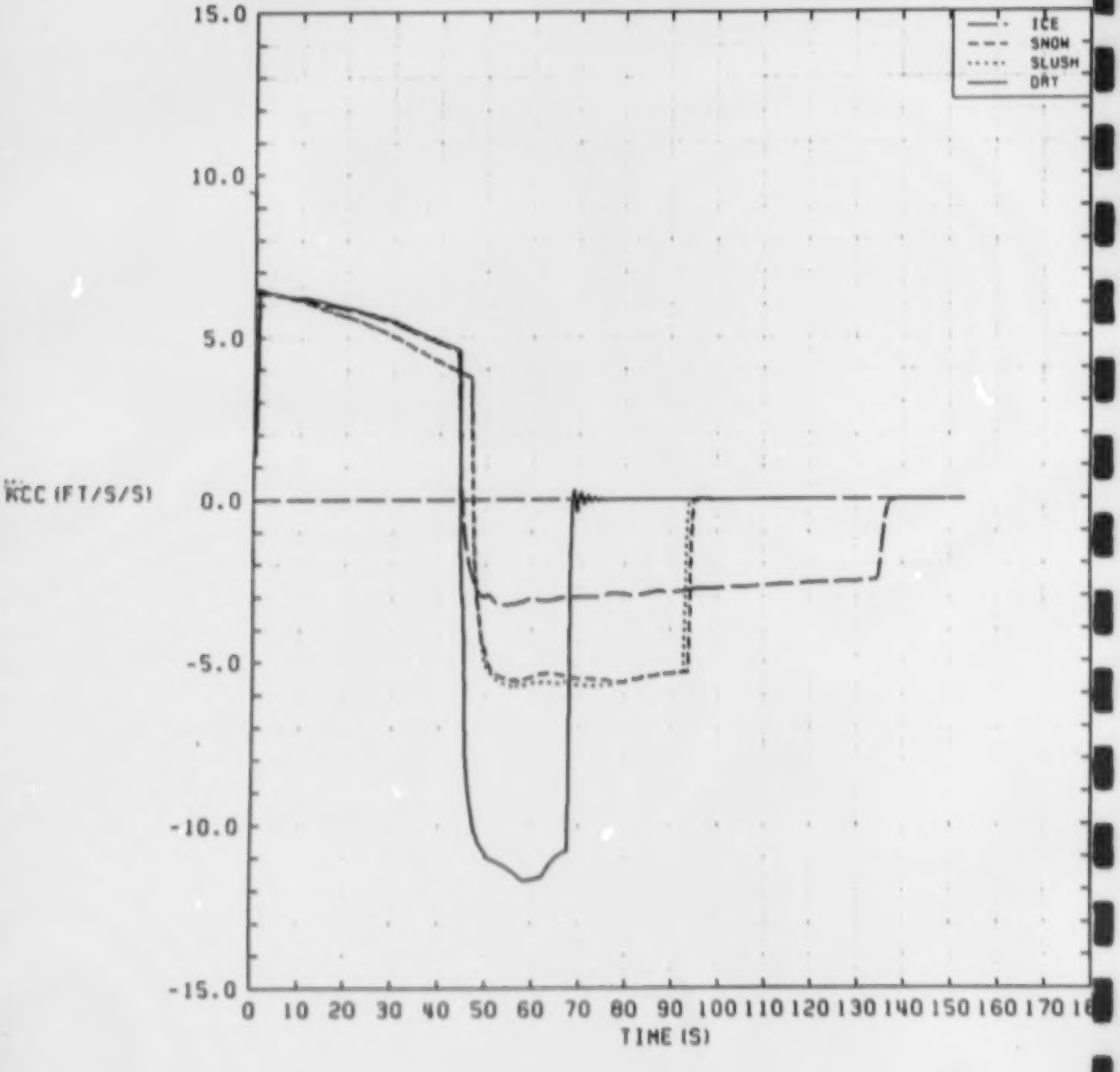
CASE = 2 ACC/STOP FOR 530000, -2C, 3500 FT.



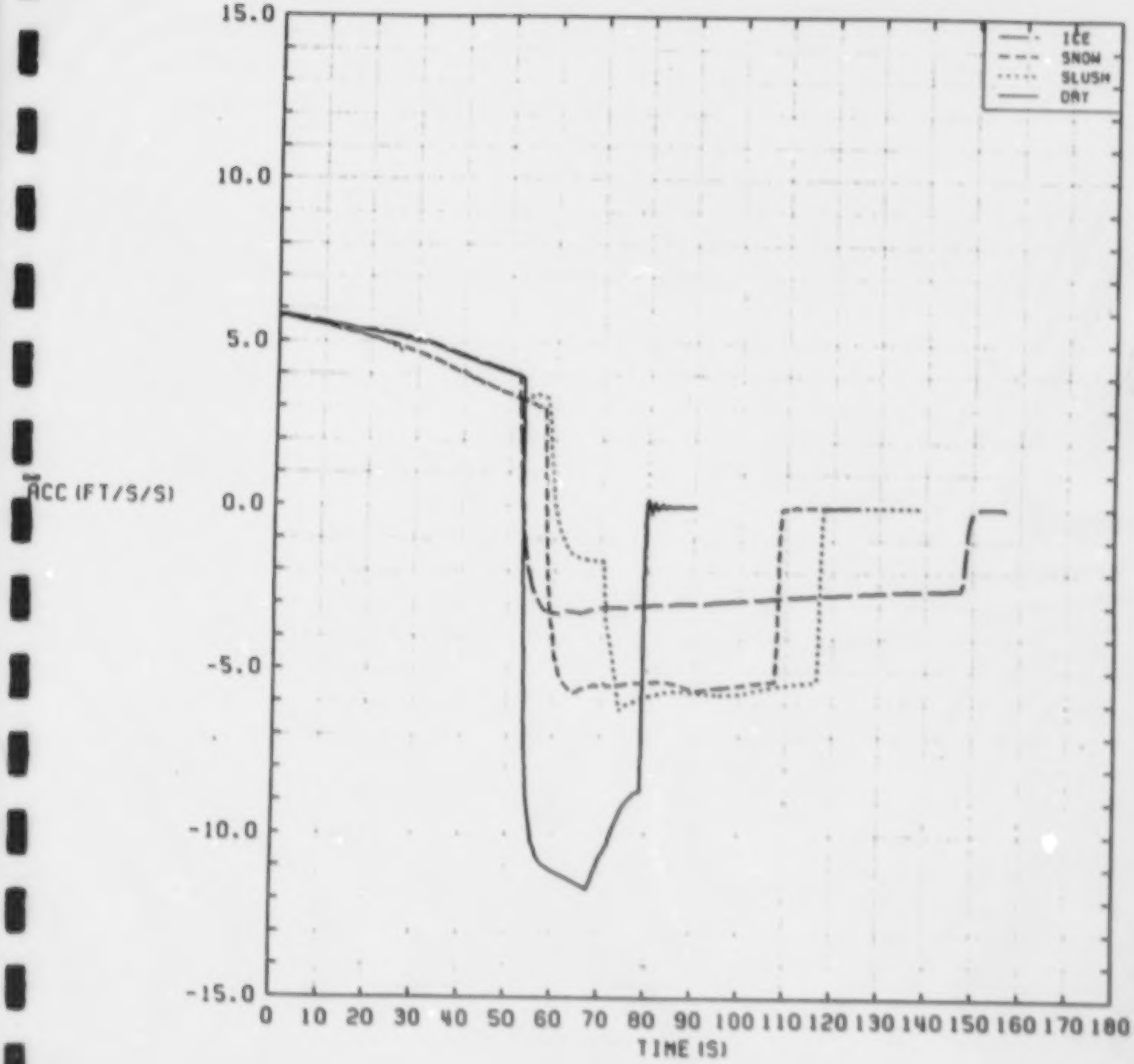
CASE=3 ACC/STOP FOR S30000, 27C, 500 FT.



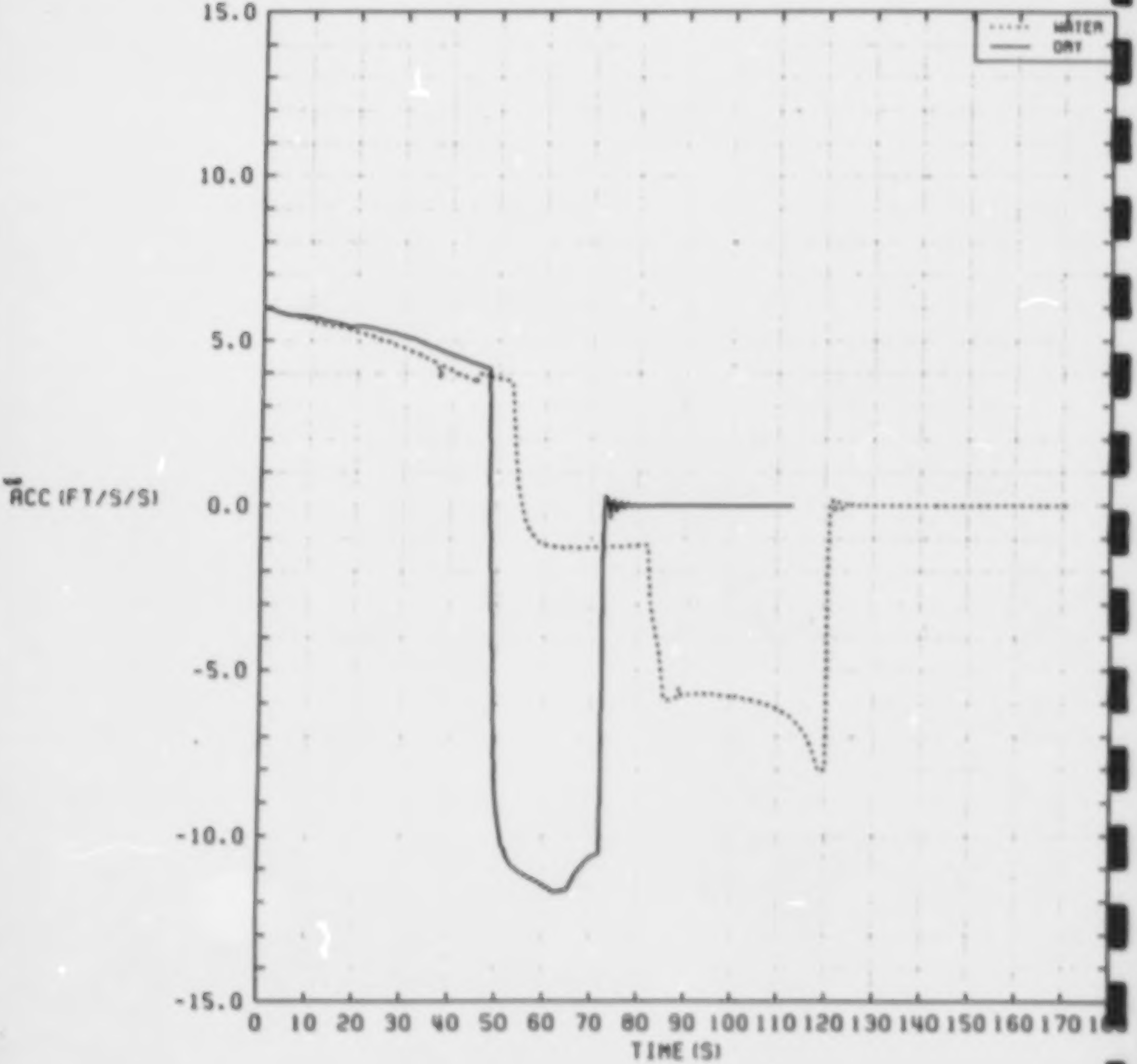
CASE= 4 ACC/STOP FOR 530000, 27C, 3500 FT.



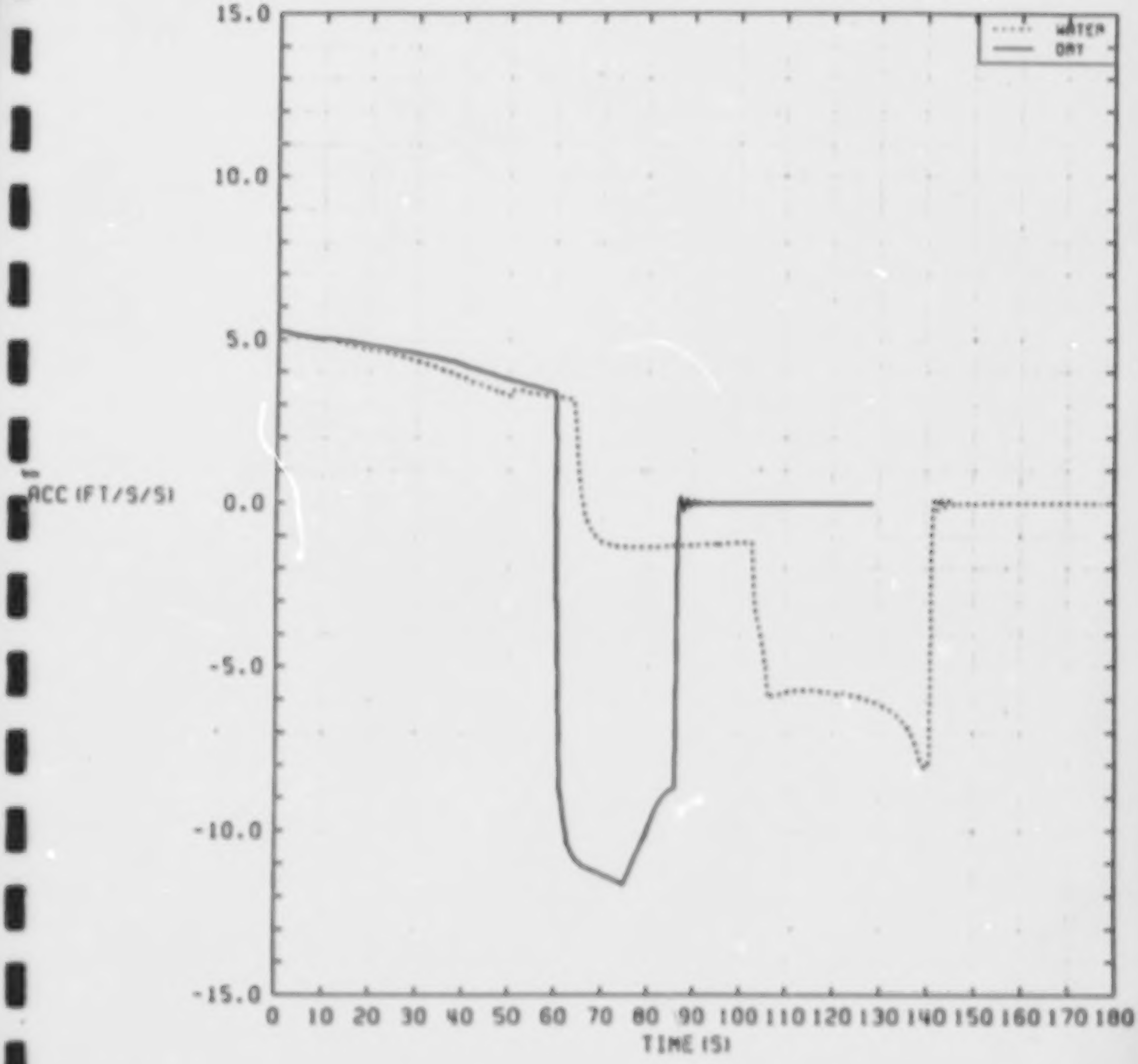
CASE = 5 ACC/STOP FOR 680000, -2C, 500 FT.



CASE•6 ACC/STOP FOR 680000, -2C, 3500 FT.



CASE= 7 ACC/STOP FOR 680000, 27C, 500 FT.



CASE•8 ACC/STOP FOR 680000, 27C, 3500 FT.

Pilot AB Date April 17/90

Headwind 4.0 (Kts) A/C mass 530,000 (lbs) Alt 3500 (ft)

EPR 1.43 V_1 127 V_R 133 V_2 143 V_{35} 149

Flap 10° Trim +3 Gear Down. OAT -2°C

Run No.	Time	File Name	Fluid Ht(mm)	Warn Spd(kts)	Max µ	Fluid s.g.	Hydroplane (1)/(0)	Comments
34	9:31	AB034	0	127	0.6	1.0	0	ASD - 6035.6
35	9:37	AB035	0	133	0.6	1.0	0	TOD - 5496.3
36	9:46	ABB035	0	133	0.6	1.0	0	TOD - 5619 [illegible]
37	9:45	AB037	8	127	0.2	0.78	1	ASD - [illegible] stops ?
38	9:48	AB038	8	127	0.2	0.75	1	(1900) ASD - 9157.2
39	9:52	AB039	8	133	0.2	0.18	1	TOD - 5989.6
40	9:57	AB040	20	127	0.2	0.3	1 (0 [illegible])	- 9160.9
41	10:01	AB041	20	133	0.2	0.3	1 ([illegible])	TOD - 6134.1
42	10:05	AB042	0	127	0.1	10	0	ASD - 13465.7

Pilot AB Date April 17/90

Headwind 3.5 (Kts) A/C mass 530,000 (lbs) Alt 3500 (ft)

EPR 1.36 V_1 127 V_R 134 V_2 143 V_{35} 149

Flap 10° Trim +3 Gear Down. OAT 27 °C

Run No.	Time	File Name	Fluid Ht(mm)	Warn Spd(kts)	Max µ	Fluid s.g.	Hydroplane (1)/(0)	Comments
43	10:10	AB042	0	127	0.6	1.0	0	* wrong wind speed (=0) ASD - 6620.0
44	10:15	AB0043	0	127	0.6	1.0	0	ASD - 6685.8
45	10:17	AB0044	0	134	0.6	1.0	0	TOD - 7059.7
46	10:22	AB0045	6	127	0.3	1.0	1	ASD - 9588.6
47	10:25	AB0046	6	134	0.3	1.0	1	TOD - 7331.1

Pilot AB Date April 17/90
Headwind 3.5 (Kts) A/C mass 53000 (lbs) Alt 3500 (ft)
EPR 1.36 V_1 110 V_R 134 V_2 ______ V_{35} 149 V_1
Flap 10° Trim +3 Gear Down. OAT 27°C

Run No.	Time	File Name	Fluid Ht(mm)	Warn Spd(kts)	Max µ	Fluid s.g.	Hydroplane (1)/(0)	Comments
48	10 [illegible]	STRONG ~~ABC0047~~	6	110	0.3	1.0	1	ASD - 7071.7
49	10.35	ABC0048	6	134	0.3	1.0	1	L.ENG. FAIL TOD - 8767.6

Pilot AB Date April 17/90

Headwind 3.5 (Kts) A/C mass 680,000 (lbs) Alt 3500 (ft)

EPR 1.42 V_1 153 V_R 159 V_2 165 V_{35} 173

Flap 10° Trim +3 Gear Down. OAT -2°C

Run No.	Time	File Name	Fluid Ht(mm)	Warn Spd(kts)	Max µ	Fluid s.g.	Hydroplane (1)/(0)	Comments
50	11:00	AB0049	0	153	0.6	1.0	0	ASD - [illegible] (0-)
51	11:05	AB0050	0	153	0.6	1.0	0	ASD - 11134.3
52	11:07	AB0051	0	159	0.6	1.0	0	TOD - 13775.9
53	11:12	AB0052	8	153	0.2	0.75	1	ASD - 18197.7
54	11:17	AB0053	8	159	0.2	0.75	1	TOD 11809.1
55	11:20	AB0054	20	153	0.2	0.3	0	ASD - [illegible] good!
56	11:25	AB0055*	20	153	0.2	0.3	0	ASD - 15604.0
57	11:28	AB0056*	20	159	0.2	0.3	0	TOD 12 057.6
58	11:32	AB0057	0	153	0.1	1.0	0	ASD Too low [illegible]
59	11:37	AB0058	0	153	0.1	1.0	0	ASD 20216 5
60								

Pilot AB Date April 17/90

Headwind 3.5 (Kts) A/C mass 680,000 (lbs) Alt: 3500 (ft)

EPR 1.37 V_1 154 V_R 160 V_2 165 V_{35} 173

Flap 10° Trim +3 Gear Down. OAT 27°C

Run No.	Time	File Name	Fluid Ht(mm)	Warn Spd(kts)	Max µ	Fluid s.g.	Hydroplane (1)/(0)	Comments
60	11:42	AB0059	0	154	0.6	1.0	0	ASD - 12252.4
61	11:45	AB0060	0	160	0.6	1.0	0	TOD - 11879.7
62	11:50	AB0061	6	154	0.3	1.0	1	ASD 24189.9
63	11:55	AB0062	6	160	0.3	1.0	1	TOD - 12925.3

Pilot AB Date April 17/90

Headwind 3.0 (Kts) A/C mass 530000 (lbs) Alt 500 (ft)

EPR 1.39 V_1 123 V_R 131 V_2 143 V_{35} 149

Flap 10° Trim +3 Gear Down. OAT −2°C

Run No.	Time	File Name	Fluid Ht(mm)	Warn Spd(kts)	Max µ	Fluid s.g.	Hydroplane (1)/(0)	Comments
64	1:15	AB0063	0	123	0.6	1.0	0	ASD - 5025.9
65	1:20	AB0064	0	131	0.6	1.0	0	TOD · 4809.3
66	1:26	AB0065	0	123	0.3	1.0	0	ASD - 6153.1 ·
67	1:29	AB0066	0	123	0.2	1.0	0	~~AS~~D · 7530.0 ·
68	1:31	AB0067	0	131	0.2	1.0	0	TOD - 5053.1
69	1:33	AB0068	8	123	0.2	0.78	1	ASD - 7643.6 ·
70	1:37	AB0069	8	131	0.2	0.78	1	TOD · 5499.6
71	1:40	AB0070	20	123	0.2	0.3	0	ASD · 7734.2 ·
72	1:43	AB0071	20	131	0.2	0.3	0	TOD - 5477.0
73	1:46	AB0072	0	123	0.1	1.0	0	ASD - did not stop
74	1:48	AB0073	0	123	0.1	1.0	0	ASD "again"
75	1:52	AB0074	0	123	0.1	1.0	0	ASD 11737.0 ·

Pilot____________ Date__________

Headwind 3.5 (Kts) A/C mass 530 000 (lbs) Alt 500 (ft)

EPR 1.31 V_1 123 V_R 130 V_2 143 V_{35} 149

Flap 10° Trim +3 Gear Down. OAT 27°C

Run No.	Time	File Name	Fluid Ht(mm)	Warn Spd(kts)	Max µ	Fluid s.g.	Hydroplane (1)/(0)	Comments
76	156	AB0075	0	123	0.6	1.0	0	ASD - 5602.6
77	159	AB0076	0	130	0.6	1.0	0	TOD - 6018.4
78	202	AB0077	6	123	0.3	1.0	1	ASD - 8029.2
79	205	AB0078	6	130	0.3	1.0	1	TOD - [illegible] 6470.3

Pilot AB Date April 17/90

Headwind 4.5 (Kts) A/C mass 680 000 (lbs) Alt 500 (ft)

EPR 1.41 V_1 151 V_R 158 V_2 165 V_{35} 173

Flap 10° Trim +3 Gear Down. OAT −2°C

Run No.	Time	File Name	Fluid Ht(mm)	Warn Spd(kts)	Max µ	Fluid s.g.	Hydroplane (1)/(0)	Comments
80		AB0079						do good [illegible]
81	2:36	AB0080	0	151	0.6	1.0	0	ASD 8968.8
82	2:40	AB0081	0	158	0.6	1.0	0	TOD 8320.0
83	2:45	AB0082	0	151	0.3	1.0	0	ASD 10120.5
84	2:49	AB0083	0	151	0.2	1.0	0	ASD 12153.9
85	2:51	AB0084	0	158	0.2	1.0	0	TOD 8809.7
86	2:54	AB0085	8 0	151	0.2	0.78	1	12[illegible] ASD 12467.3
87	2:57	AB0086	8	158	0.2	0.78	1	TOD 9550.6
86	3:03	AB0087	20	151	0.2	0.3	0	ASD 12632.4
87	3:05	AB0088	20	158	0.2	0.3	0	TOD 9446.0
89	3:10	AB0089	0	151	0.1	1.0	0	ASD 17330.4

Pilot AB Date April 17/90

Headwind 4.5 (Kts) A/C mass 680 000 (lbs) Alt 500 (ft)

EPR 1.41 V_1 151 V_R 158 V_2 165 V_{35} 173

Flap 10° Trim +3 Gear Down. OAT −2°C

Run No.	Time	File Name	Fluid Ht(mm)	Warn Spd(kts)	Max μ	Fluid s.g.	Hydroplane (1)/(0)	Comments
80		AB0079						no good (autopilot wrong?!)
81	2:36	AB0080	0	151	0.6	1.0	0	ASD 8964.8
82	2:40	AB0081	0	158	0.6	1.0	0	TOD 8320.0
83	2:45	AB0082	0	151	0.3	1.0	0	ASD 10120.5
84	2:49	AB0083	0	151	0.2	1.0	0	ASD 12153.9
85	2:51	AB0084	0	158	0.2	1.0	0	TOD 8809.7
86	3:54	[illegible]	8	151	0.2	[illegible]	1	[illegible] ASD [illegible]
87	[illegible]	[illegible]	[illegible]	[illegible]	0.2	[illegible]	1	[illegible]
[illegible]					[illegible]		[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]								

Pilot AB Date April 17/96

Headwind 2.5 (Kts) A/C mass 680 000 (lbs) Alt 500 (ft)

EPR 1.37 V_1 152 V_R 158 V_2 165 V_{35} 173

Flap 10° Trim +3 Gear Down. OAT 27°C

Run No.	Time	File Name	Fluid Ht(mm)	Warn Spd(kts)	Max μ	Fluid s.g.	Hydroplane (1)/(0)	Comments
89	3	AB0090	0	152	0.6	1.0	0	1.151 – [illegible]
90	3:15	AB0091	0	152	0.6	1.0	0	ABD - 9525.0
91	3:20	AB0092	0	158	0.6	1.0	0	TOD - 5940.6
92	3:23	AB0093	6	152	0.3	1.0	1	ABD - 19381.8
93	3:26	AB0094	6	158	0.3	1.0	1	TOD ~~[illegible]~~ 10172.4

2.

RECEIVED
MAY - 9 [illegible]

BAKER AVIATION SERVICES LIMITED
5629 Dalcastle Hill N.W.
Calgary, AB
T3A 2A2

EVALUATION REPORT

AIRCRAFT TAKEOFF PERFORMANCE ON WET RUNWAYS

Prepared: ______________ 1 May 90

Reviewed: ______________ ______________

Approved: ______________ ______________

Revision	Report Number	Page

1.0 PURPOSE

This Report assesses the University of Toronto Institute of Aerospace Studies (UTIAS) flight simulator as a tool for evaluating contaminated runway takeoff performance, and provides an initial qualitative assessment of the major performance problem.

2.0 SCOPE

The scope was limited to all engines operating takeoffs and rejected takeoffs on simulated dry, wet, slush, ice and snow covered runways. Qualitative aspects only are addressed in this Report.

3.0 FLIGHT SIMULATOR

The CAE Series 300 flight simulator was a consisted of a DC-8 cab mounted on a six degree of freedom motion base. The motion system was inoperative. A three-window visual display was fitted showing a textured runway approximately 12000 feet long with center-line and edge lights in a dawn (or dusk) environment. For some of the tests, only the center window was operative. The simulator was programmed to represent a Boeing 747 airplane.

4.0 TAKEOFF SPEEDS

The takeoff speeds V_1, V_R, and V_2 were taken from the Boeing 747 Airplane Flight Manual (AFM). As the scope was limited to all engines operating, a target all engines operating 35 foot screen height speed of $1.25V_R$ was arbitrarily chosen, representative of low thrust-to-weight performance.

5.0 ALL ENGINES TAKEOFF

5.1 Test Procedure. To obtain consistent and comparable results, the "engines" were set at the target takeoff thrust before brake release. After brake release, the thrust was adjusted to the target value at 60 to 80 knots. A horn provided a reminder of V_R at which time a smooth, steady rotation was initiated to the initial climb attitude such that the airplane would pass through the 35 foot screen height at the target speed. Once the takeoff was complete, the simulator was frozen, then re-positioned for the next exercise.

5.2 Test Results. The takeoff maneuver was easy to carry out. There was a tendency for an oscillation in yaw to develop during the takeoff roll, but the runway centerline could be maintained with a tolerable workload. The rotation was realistic and the target speeds were achieved with the usual scatter due to pilot technique. There was a tendency for a roll oscillation to develop after takeoff, but this required only mild pilot effort to control. Qualitatively, the takeoff distances compared favourably with those published in the AFM. Qualitatively the runway contaminants had little effect on the continued takeoff distance.

5.3 Discussion of Results. The yaw and roll oscillations were probably pilot-induced and due to lag in the response of the visual display. Although the all engines takeoff distances compared with those in the AFM, care must be taken to ensure that a proper comparison is being made. The AFM distance is the greater of the one engine inoperative distance or 115% of the all engines distance. The AFM also includes only 50% of the headwind at the height of the wing mean aerodynamic chord. To ensure that the simulator model is reflecting reality, it should be confirmed that these factors have been removed. It should not be expected that the all engines distances measured in the simulator compare to the AFM. They should be shorter.

It is not surprising that the runway contaminants had little effect on the continued takeoff distance. When the size of the airplane and its wheels are compared to the depth of contaminant, it is apparent that any effect would be minimal.

5.4 Conclusions. The flight simulator was satisfactory for examining the effect of contaminants on the all engines continued takeoff distance. If direct comparison with the AFM is required, it should be confirmed that AFM factors have been removed to ensure as accurate a comparison as possible.

6.0 ACCELERATE-STOP DISTANCE

6.1 Test Procedures. For good comparison with the continued takeoff and to ensure consistency, the engines were set at target takeoff thrust before brake release. Final thrust adjustments were made at 60 to 80 knots. At the decision speed, a horn sounded. The takeoff was then rejected by applying maximum braking and simultaneously reducing thrust to idle as rapidly as possible. The ground spoilers were extended automatically. No attempt was made to simulate the time delays for pilot recognition and action incorporated in the AFM expansion. No reverse thrust was used. Maximum braking was applied until the airplane came to a stop. Once the accelerate-stop was complete, the simulator was frozen, then re-positioned for the next exercise.

6.2 Test Results. The accelerate-stop maneuver was reasonably easy to carry out. Directional control was somewhat difficult as corrections in yaw needed to be made carefully to avoid a yaw oscillation. The brakes were difficult to apply fully for the period of time required. Full brake application required high forces and the brake pedal geometry was awkward. Qualitatively, the accelerate-stop distances on a dry runway compared favorably with those in the AFM and with the continued takeoff. On contaminated runways, the distances were noticeably increased. Where hydro-planing occurred, or with low friction coefficients, the increase was dramatic.

6.3 Discussion of Results. The slight difficulty in maintaining precise directional control was probably due to lag in the visual display. Brake forces and geometry are a function of the DC-8 cab. Nevertheless, the simulator was adequate for making the all engines accelerate-stop distance comparison.

The approximately equal continued takeoff and accelerate-stop distances and the good comparison with the AFM provided confidence in the computer airplane model. The comments in para. 5.3 regarding the factors on the AFM takeoff distance should be addressed. In addition, with no time delays for pilot action in actuating the retardation devices and the automatic ground spoilers, the measured accelerate-stop distance on the dry runway should be less than the AFM distance. If direct comparison with the AFM is required to provide credibility in the airplane computer model, then these time delays should be taken into consideration.

It was very obvious that the main risk involved in operating from contaminated runways was the difficulty stopping from at or near the decision speed, V_1.

6.4 Conclusions. The flight simulator was satisfactory for examining the effect of contaminants on the all engines accelerate-stop distance. In addressing the risk involved in operating from contaminated runways, the greatest factor is the inability to stop quickly from the decision speed, V_1.

7.0 CHARACTERISTICS TO BE ADDRESSED

Initial, qualitative results would indicate that the main problem with operation from contaminated runways is the difficulty stopping in the event of a decision to abort the takeoff from speeds at, or near V_1. If the problems of hydroplaning and very slippery runways are to be realistically addressed, it is very evident that means other than wheel braking must be used. The effect of reverse thrust was not evaluated in these preliminary tests, but should be considered for all subsequent evaluations. The safety, reliability, consistency and controllability with reverse thrust (symmetric and asymmetric) should be evaluated. Reverse thrust should be made operable in the simulator for subsequent work.

It was equally apparent that a reduction in the decision speed, V_1, would improve the stopping capability by reducing the kinetic energy to be dissipated, reducing the hydroplaning problem, and increasing the distance available for stopping. Too much of a reduction in V_1, however, is operationally unacceptable. The screen height at the end of the takeoff distance in the event of a continued takeoff with one engine inoperative needs to be adequate. Even 35 feet does not seem much for a B747! Also, from the psychological point of view, a long acceleration time from V_1 to V_R with an engine inoperative is very unnatural and may result in pilots taking stopping action after V_1.

8.0 SUMMARY

The fixed-base simulator was adequate for assessing the effect of contaminated runways for continued takeoff and accelerate-stop distances with all engines operating. For the one engine inoperative continued takeoff or accelerate-stop, a motion system is highly desirable to provide the pilot with acceleration cues to provide realistic reaction times and for assessment of controllability. Reverse thrust must be activated.

The main problem in operating a large airplane from a contaminated runway is the difficulty stopping in the event of a decision at, or near, V_1.

From the airplane operational point of view, items to be addressed are the capability of providing retarding means other than wheel brakes and the scheduling of takeoff speeds to provide increased stopping distance.

APPENDIX E

DETAILED DESCRIPTION OF RISK MODEL PROGRAM

E1. Introduction

The risk model program calculates the probability distribution of the margins of safety available on take-off under various conditions for a given aircraft type and a given airport. The program takes into account the distribution of take-off weights, wind speed and direction, temperature and altitude effect on air pressure, number of departures on each runway, runway conditions, and type and timing of critical events on take-off. In addition, the effect of reverse thrust and variable pilot response time in aborted take-offs are shown. Aircraft performance data and runway characteristics are also used by the program when determining the margin of safety.

The program computes the proportion of departures at maximum and actual take-off weight for which take-off weight is restricted due to available runway length. It also produces tables of the distribution of the margin of safety or additional runway required for the following conditions:

(a) dry conditions, allowed maximum take-off weight (ATOW), critical event at V_1, all engines operating for aborted take-offs, engine failure for continued take-offs, table for aborted and continued take-offs;

(b) as in (a), except that actual take-off weight is used;

(c) actual runway conditions, critical event at V_1 (as in (a)), actual take-off weight, table for aborted and continued take-offs;

(d) as in (c), except that reverse thrust is used, table for aborted take-offs;

(e) actual runway conditions, actual type and time of critical event, actual take-off weight, table for aborted and continued take-offs;

(f) as in (e), except that variable pilot response time is allowed, table for aborted take-offs.

The program is written in FORTRAN and compiled using Microsoft FORTRAN. The data files for a given aircraft and airport are constructed by a DBASE program from various database files. Databases for the following airports and aircraft types are available for running the risk analysis program:

Airports: Ottawa International
Halifax International
Toronto International

Calgary International
Edmonton Municipal
Prince George

Aircraft Types:	B747 A320 BA146

Toronto runway condition data is not available and the program uses Ottawa data instead. It is recognized that Ottawa conditions are likely to be worse than Pearson because of more extreme climate conditions, and that therefore the substitution creates a "worst case" for Toronto.

The remainder of this appendix makes use of a number of symbols which are defined in a glossary of symbols in Section E11.

E2. Methodology For Risk Analysis Program

The risk analysis uses a probabilistic approach to determine the risk of an overshoot accident or failure of the aircraft to clear a 35 foot screen height at the end of the runway. The probabilistic approach and the characteristics affecting accelerate-stop and take-off distances are described in Section 5.5. A flow chart showing the steps used to determine the margin of safety and the additional runway required for a particular aircraft and airport are shown in Figure E1. The method used to estimation of accelerate-stop and take-off distances is described below.

The accelerate-stop (ASD) and take-off (TOD) distances for dry runway conditions and a critical event occurring at V_1 can be found using the aircraft flight manual (AFM). The effect of the characteristics, wind direction (WD), wind speed (WS), temperature (T), take-off weight (TOW) and critical event (CE) given in Table 5-14 and airport/runway characteristics such as runway gradient and air pressure due to altitude can be determined. However, it is not feasible to calculate the ASD and TOD for each combination of characteristics from the flight manual for inclusion in the risk analyses as there are an extremely large number of combinations. Therefore, a model was developed for calculating ASD and TOD based on several simplifying assumptions.

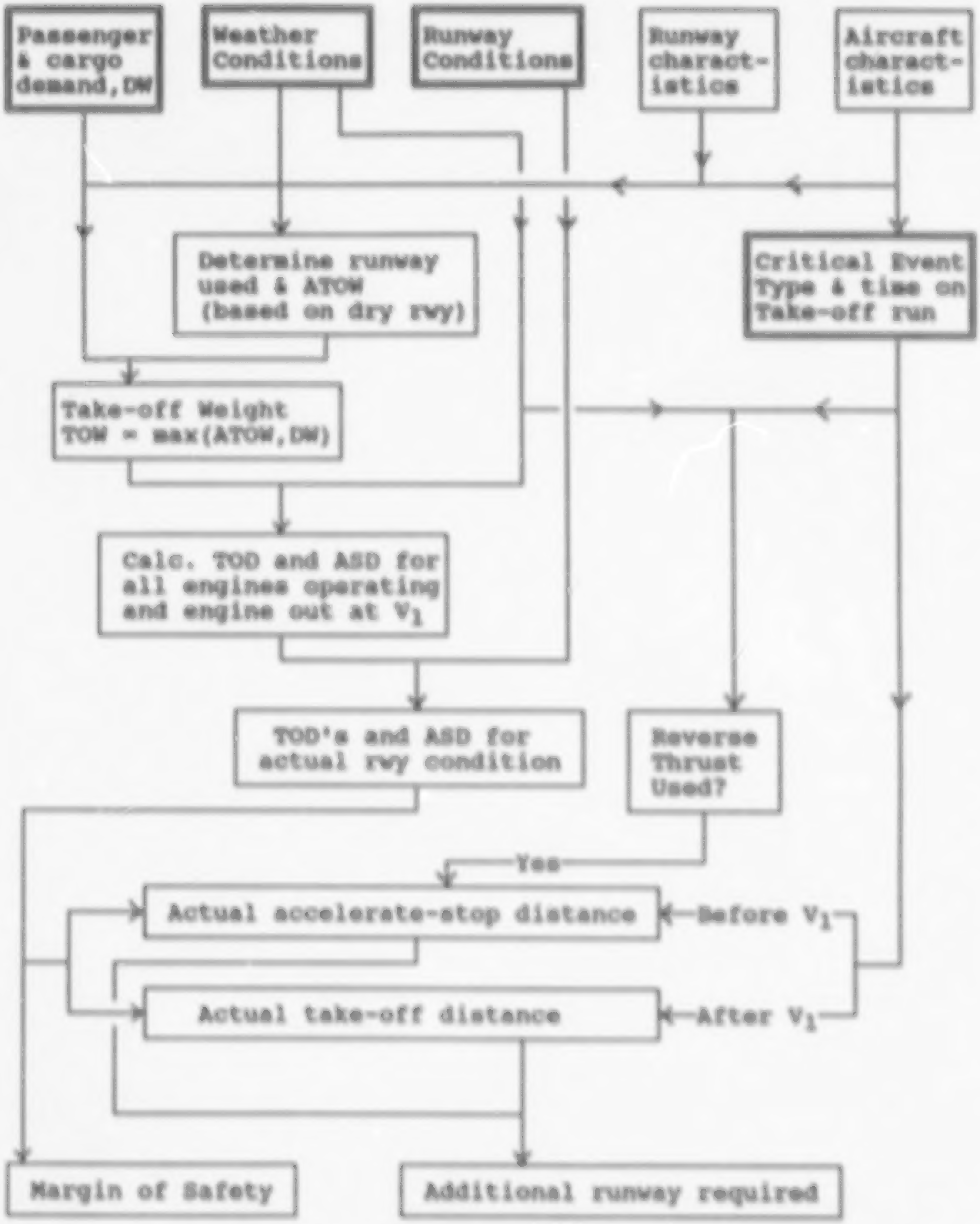

Passenger & cargo demand, DW
Weather Conditions
Runway Conditions
Runway characteristics
Aircraft characteristics
Determine runway used & ATOW (based on dry rwy)
Critical Event Type & time on Take-off run
Take-off Weight TOW = max(ATOW,DW)
Calc. TOD and ASD for all engines operating and engine out at V_1
TOD's and ASD for actual rwy condition
Reverse Thrust Used?
Yes
Actual accelerate-stop distance
Before V_1
Actual take-off distance
After V_1
Margin of Safety
Additional runway required

Figure E1 Flow Chart for the Estimation of Margin of Safety and Additional Runway Required for a Particular Aircraft and Airport

This model for estimating ASD and TOD is a simple mathematical representation of a very complex system and only provides approximate values of ASD and TOD under various conditions. It was assumed that most of the various characteristics act independently and that each affects the ASD and TOD by proportionally increasing, or decreasing, the ASD and TOD. Starting with a value of ASD and TOD at a set of standard conditions, the value is adjusted up or down according to the amount by which each characteristic differs from the standard conditions. The functional form used in the model was chosen after consideration of many graphs of ASD and TOD versus various take-off conditions in the B747 and BA146 AFM's. Specifically, ASD is estimated as follows:

$$ASD = ASD_0\ C_a^{ALT}\ C_g^{GRD}\ C_t^{T}\ C_h^{HW}\ C_l^{TL}\ C_w^{\%UMTOW}\ C_r(RC)\ C_e^{CE} \qquad (1)$$

where ASD_0 is the ASD at sea level, 0^0C, on a flat runway, with zero head wind, at MTOW, on a dry runway and when the critical event is not an engine failure,
ALT is the altitude of the runway in '000 feet,
GRD is the percentage gradient of the runway,
T is the temperature in ^{0}C,
HW is the head wind in knots,
TL is the tail wind in knots,
%UMTOW is the percentage that take-off weight is under certified MTOW,
C_r(CR) is the adjustment factor for the runway condition, RC,
CE is the type of critical event (1 for engine failure, 0 otherwise),

C_a, C_g, C_t, C_h, C_l, C_w and C_e are constants related to the accelerate-stop distance for a particular aircraft type.

Similarly, TOD is estimated by:

$$TOD = TOD_0\ K_a^{ALT}\ K_g^{GRD}\ K_t^{T}\ K_h^{HW}\ K_l^{TL}\ K_w^{\%UMTOW}\ K_r(RC)\ K_e^{CE} \qquad (2)$$

where K_a, K_g, K_t, K_h, K_l, K_w and K_e are constants related to the take-off distance for a particular aircraft type.

The proportional increase in TOD when the critical event is an engine failure is assumed to be related to the TOW since the effect of TOW on TOD is much greater when the aircraft is fully loaded than when it is empty.

The parameters in the model were calibrated using either data from the AFM or aircraft performance data obtained from a simulator. The effect of runway condition on ASD and TOD is not required in the AFM in Canada or the U.S., but it is required to be supplied as supplementary material to the AFM in the JARS regulations. Using this supplementary material, the effects of contaminated runways on ASD and TOD were calculated for the A320 and BA146 aircraft. The UTIAS simulator was used to determine the effects of contaminated runways for the B747. Linear regression of the logarithms of Equations (1) and (2) was used to determine the parameters $C_a, \ldots, C_e$ and $K_a, \ldots, K_e$.

Let AD be the accelerate-stop distance and TD be the take-off distances for a departure under actual runway conditions and where a critical event need not occur at V_1 speed. ASD and TOD are the values of AD and TD for a dry runway and a critical event at V_1.

The AD and TD for critical events occurring at times other than V_1 were calculated by assuming a simple model of the acceleration-deceleration profile discussed in Section E7.2. The effect of a variable response time was included by adjusting the ASD by the distance travelled during the difference in response time from that time used in AFM (2 seconds) assuming the aircraft travels at the same speed at the time of the critical event.

The effect of reverse thrust on the AD distance was modelled using the assumption that it will proportionally decrease the AD. This proportion is allowed to vary with runway condition, thus on an icy or flooded runway the effect of reverse thrust is greater than on a dry runway. When the critical event occurs before V_1, the response time is variable and reverse thrust may be used, AD is calculated as follows:

$$AD = ASD\ C_{et}\ C_{rev}^{REV} + 1.686\ (t_r - 2)\ V_e \qquad (3)$$

where ASD is found from Equation (1),
C_{et} is the adjustment factor for AD when the critical event occurs at time t,
C_{rev} is the adjustment factor for the use of reverse thrust,
REV = 1 if reverse thrust is used, 0 otherwise
t_r is the pilot response time in seconds, and
V_e is the speed at the time of the critical event in knots and the factor, 1.686, converts knots to ft/s.

Similarly, the TD when the critical event occurs after V_1 is found by,

$$TD = TOD\ K_{et} \qquad (4)$$

where TOD is found from Equation (2), and
K_{et} is the adjustment factor for TD when the critical event occurs at time t,

Details on the use of each characteristic in the risk model and calculation of the factors are given in the following sections. The models were found to predict the AD and TD to within 5% of their actual value (based on AFM and simulator tests) in 3/4 of the accelerate-stop and take-off cases tested. The accuracy of the model for predicting AD and TD is discussed in Section E10.

E3. Legal Requirements On Accelerate-stop And Take-off Distances

In the model all departures must satisfy the legal requirements that:

- ASDA, the accelerate stop distance available, is greater than ASD, the accelerate-stop distance on a dry runway when the take-off is aborted at V_1 (due to either engine failure or another type of critical event and reverse thrust is not used), and
- TODA, the available take-off distance, is greater than:
  - the distance required to clear a 35 foot screen on a dry runway, if an engine failure occurs at V_1, and
  - 1.15 times the distance required to clear a 35 foot screen on a dry runway when no engine failure occurs.

If these conditions are not satisfied, the longest runway is used, wind conditions permitting, and/or the TOW is reduced. Changes in the V_1 speed are not considered, nor are allowances made for clearways and stopways.

The effect of changes in the legal requirements (see discussion on countermeasures, Section 7.2) can be determined by adjusting these legal requirements within the program and determining the change in the distribution of the margin of safety and expected number of accidents.

E4. Weather Conditions And Choice Of Runway

Weather condition data was obtained from Environment Canada for each of the airports considered. The data were obtained in the form of frequency counts of particular conditions at particular times over the years 1953 to 1988. The frequency data was then converted to probabilities for use in the risk analyses.

Temperature variation by month and time of day was modelled using the probability distribution of temperatures for a particular month and time of day. Two hour intervals for time of day were used and the range of temperatures (°C) were divided into the following 7 categories:

< -30
-30 to -20
-20 to -10
-10 to 0
0 to 25
25 to 30
> 30

The joint probability distribution of wind speed and direction for each month was used to allow for the variation in wind conditions. Sixteen wind direction categories and eight wind speed categories plus another category for calm conditions were used.

The head wind and crosswind components of wind were calculated for each runway as shown in Figure E2. The head wind, HW, and crosswind, CW, were calculated by:

$$HW = WS \cos(\phi - \theta)$$
$$CW = WS \sin(\phi - \theta)$$

where WS is the wind speed,
ϕ is the runway direction (see Figure E2), and
θ is the wind direction (see Figure E2).

The choice of runway is based on guidelines for airport control provided by Transport Canada (Air Traffic Control Manual of Operations TP 703, Part 3 Airport Control). For wind speeds of more than 5 knots, departures were assigned to the runway most nearly aligned into the wind, or, equivalently, the runway with the greatest head wind. For head winds of less than 5 knots, the following method was used:

- if aircraft TOW is runway restricted, the main (longest) runway was chosen and the direction chosen so there is a head wind, otherwise

- the runway was assigned so that the distribution of departures most closely matches the observed distribution of departures on the available runways.

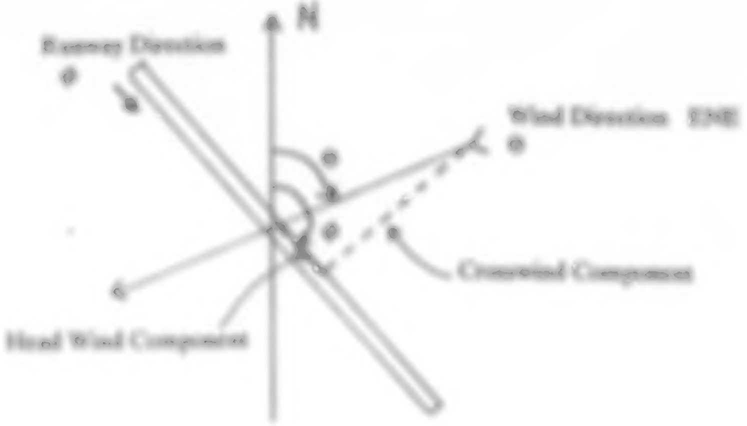


Figure E2 Calculation of Head Wind and Crosswind for a Given Wind Speed and Direction and Runway

E5 Take-off Weights

E5.1 Aircraft Weight Demand

The aircraft take-off demand weight, DW, is the total TOW including the weight of the aircraft and fuel, passengers and their baggage and any cargo booked or scheduled in advance to go on the flight. It is assumed that the typical ATOW of the aircraft at that runway and during that time of the year will be taken into account when the number of passengers and the amount of cargo is booked or scheduled for the flight. The demand weight was estimated from the aircraft weight, available weight capacity for passengers and cargo and the actual number of passengers and weight of cargo, based on data obtained from Statistics Canada. The sample of data included all departures by jet aircraft during the first seven days of each month using the most recent 12 months of data available (1988/89).

The instructions for recording the value of available weight capacity specifies that it should include the effect of the length of flight (which affects fuel load), environmental conditions and runway choice at ATOW and, thus, available weight capacity. However, it appears from the data that the reported available weight capacity generally does not take into account the weather conditions and range of the flight. Most aircraft have a standard minimum fuel load which is sufficient for most typical flight ranges and it appears that most recorded values allow for this standard fuel load. In determining the weight demand it was assumed that the weight capacity values account for this fuel load.

The Statistics Canada data give no any indication of the amount of extra fuel that is carried above that required for the flight, and the corresponding weight penalty. The "tankering" of fuel is standard policy for some carriers from some airports and contributed to the only wet runway take-off accident of jet aircraft in Canada since 1976 (CASB Report NO. 86-A60024). The accident risk probabilities are only applicable to the situation where no "tankering" of fuel takes place.

An average weight per passenger, including luggage, of 91 kg (200 lbs) was assumed in calculating total passenger weight. The percentage under allowed take-off weight, %UATOW, was estimated for each departures as follows:

$$\%UATOW = 100\ (WGT\_CAP - 91 \times PASS - CARGO)\ /\ MTOW$$

where WGT_CAP is the available weight capacity in kg,
PASS is the number of passengers on board,
CARGO is the weight of cargo on flight in kg, and
MTOW is the certified aircraft maximum take-off weight in kg.

This percent under allowed take-off weight was found to roughly follow a normal distribution for most aircraft. The %UATOW is based on actual take-off weights, but is assumed to reflect the weight demand on take-off. This approximation should have little affect on the estimated demand weight as the aircraft were rarely found to take-off at ATOW and thus, the effect of any truncation of the observed take-off weights to the ATOW would be minimal. As very few take-off weights were close to the ATOW, the standard deviation of %UATOW was restricted to be less than three times the average %UATOW for that time period.

The sample mean and standard deviation of %UATOW were calculated for each two hour time period during the day for the particular airport and aircraft type of interest. These estimates were then multiplied by the ratio of the mean value for that month over the yearly mean value to account for month-to-month variation in DW. The range of values of %UATOW was divided into 34 intervals and, based on the mean and standard deviation, the probability of %UATOW being in each interval was calculated using the normal distribution. The mid-point of each interval was used as the value of %UATOW for that interval.

Equations (1) and (2) require the percentage under MTOW rather than ATOW to estimate the accelerate-stop and take-off distances. The ATOW will be less than MTOW when the aircraft requires more runway at MTOW than is available. Thus %UMTOW will often be greater than %UATOW, depending on the value of the allowed take-off weight when booking and scheduling passengers and cargo. It is assumed when making the bookings that the weight capacity available for passengers and cargo will be calculated based on a typical ATOW for that airport and time of year. A typical value, ATOW*(month), is calculated, using the method outlined in Section E5.2, for each month based on the longest runway, the average temperature for that month and zero wind. The demand %UMTOW is then estimated for each month by:

$$\text{Demand }\%UMTOW = \%UATOW + 100\,(MTOW - ATOW^{*}(month))/MTOW$$

The typical allowed take-off weights have a maximum value in January and a minimum in July and these values were calculated to be (in lbs):

Airport	B747-100		A320	
	January	July	January	July
Toronto	700,700	730,000#	162,000#	162,000#
Calgary	695,300	716,800	162,000#	162,000#
Ottawa	670,900	703,600	159,900	162,000#
Halifax	646,900	674,400	151,400	159,600

# ATOW(month) equal to certified MTOW

The ATOW for the BA146 was equal to the MTOW of 82,250 lbs at the six airports considered in the study.

E5.2 Allowed Maximum Take-off Weight, ATOW

The ASD and TOD were estimated using Equations (1) and (2) for the aircraft at MTOW and dry runway conditions and actual values of altitude, gradient, temperature and head wind. As discussed in Section E3, the maximum take-off weight is runway restricted if any of the following is true:

$$ASDA < ASD \qquad (5a)$$
$$TODA < 1.15\ TOD \text{ (engine failure not critical event, CE=0)} \qquad (5b)$$
$$TODA < TOD \text{ (engine failure critical event, CE=1)} \qquad (5c)$$

If the maximum weight is restricted, the restricted weight, known as the allowed take-off weight, ATOW, is calculated as follows. Let %UMTOW1, %UMTOW2 and %UMTOW3 equal the values of %UMTOW at which the expressions (5a), (5b) and (5c), respectively, hold as equalities, rather than inequalities. Then ATOW, is given by:

$$ATOW = MTOW \left(1 - \max(\%UMTOW1, \%UMTOW2, \%UMTOW3) / 100 \right)$$

The values of %UMTOW1, %UMTOW2 and %UMTOW3 are calculated from Equations (1) and (2) as follows. From Equation (1) we have

$$ASDA = K\, C_W^{\%UMTOW1} \qquad (6)$$

where K is the product of all terms in Equation (1) other than $C_W^{\%UMTOW1}$. At MTOW (i.e. %UMTOW = 0), the accelerate-stop distance, ASDM, is

$$ASDM = K\, C_W^{0} = K$$

Thus, substituting ASDM for K in Equation (6) gives

$$ASDA = ASDM\, C_W^{\%UMTOW1}$$

$$\Rightarrow \quad \%UMTOW1 = \log(ASDA/ASDM)/\log(C_W)$$

Similarly, from Equation (2) %UMTOW2 and %UMTOW3 can be expressed as follows:

$$\%UMTOW2 = \log(\; TODA/TODM(CE=1) \;)/\log(K_W)$$

$$\%UMTOW3 = \log(\; TODA/(1.15\; TODM(CE=0)) \;)/\log(K_W)$$

where TODM(CE=i) is the TOD at MTOW calculated from Equation (2) with critical event, CE = i.

E5.3 Aircraft Take-off Weight

The actual take-off weight is set equal to the minimum of the aircraft weight demand, DW, and the allowed take-off weight, ATOW. Any excess weight demand which is above the allowed weight,

$$\text{Excess Weight} = DW - ATOW$$

is added to other departures. It is assumed that this excess weight is added to departures where the DW is just below the DW of the current departure so that the additional weight will bring these departures close to or equal to ATOW. This assumption is made as the weight demand around the time of peak demand is also likely to be high and when excess demand is redistributed to later flights, this will tend to put these later flights close to their maximum allowed weights also.

The adjustment of take-off weights is implemented as follows in the program. The program calculates the ASD and TOD for 34 weight demand categories. Starting with the highest weight demand category, the excess weight demand is calculated for category DW_i. Any excess demand is redistributed to the next highest weight demand category, DW_{i-1}. However, since the number of flights in each category differs and are proportional to the probability of a departure with DW in that category, the adjustment to the weight demand for flight in category DW_{i-1} is:

$$\text{Adjusted } DW_{i-1} = (DW_i - ATOW)\ P(DW_i)/P(DW_{i-1}) \qquad \text{if } DW_i > ATOW$$

where $P(DW_i)$ is the probability of weight demand being in category i.

The adjustments are made for each category, i, until the demand, DW_i does not exceed the allowed weight, ATOW. In practice, the adjustments are seldom made as few departures have a take-off weight demand greater than ATOW and when adjustments are made they usually only affect the higher weight demand categories.

E6. Runway Conditions

Runway condition data were collected from five airports for the extended winter period of November to March for 3 years. Based on these data and other reports (Refs 8, 10, 12, 13, 14, 47, 52, 53 and 54), a number of typical runway conditions were identified. The factor increases in ASD and TOD due to these runway conditions, $C_r(RC)$ in Equation (1) and $K_r(RC)$ in Equation (2), were estimated for the B747 from the simulator results and the A320 from the AFM computer program and for the BA146 from the Appendix to the AFM (Document BAe 3.2). The results are given in Table E1.

The values of the runway friction, μ, given in the table are those related to the aircraft braking and these are typically less (by about 30% to 70%) than that measured by a ground vehicle. The ASD values found for wet and contaminated runways from the AFM for the A320 include the effect of reverse thrust. It therefore was necessary to remove the reverse thrust effect to determine the effect of only the runway condition. The method of adjusting for the effect of reverse thrust is given in Section E8.

Table E1 Factor Increases in ASD and TOD due to Various Typical Runway Conditions

Runway Condition	μ	ASD Factors, C_r B747	A320	BA146*	TOD Factors, K_r B747	A320	BA146
Dry	0.6	1.00	1.00	1.00	1.00	1.00	1.00
Wet	0.3	1.18	1.15	1.16	1.02	0.99	1.00
Water (6 mm 1/4")	0.3	1.70	1.82	1.75	1.056	1.016	1.11
Slush (8 mm 1/3")	0.2	1.51	1.[illegible]	1.60	1.12	1.14	1.19
Compact Snow	0.2	1.43	1.46	1.45	1.046	0.924	1.0
Loose snow (20 mm 3/4")	0.2	1.46	1.65	1.55	1.13	1.15	1.10
Frost	0.2	1.43	1.46	1.45	1.046	0.924	1.0
Ice	0.1	2.07	2.07	2.07	1.046	0.924	1.0

. ASD factor values for BA146 estimated to be average of values for B747 and A320

The depth of contaminant is given in Table E1 where there is displacement and impingement drag due to the contaminant. The values for frost and compact snow are assumed to be the same as for runway condition dry with μ=0.2 and wet is assumed to be the same as for dry with μ=0.3.

The factors given in Table E1 are calculated assuming each condition is the same over the entire runway. However, the runway condition often varies considerably over the length of the runway. Also, the conditions during the acceleration and deceleration phases of an accelerate stop are unknown. Therefore, the factor for a given runway condition, RC, was calculated to be the weighted average of the factors where the weights equalled the proportion of the runway in that condition. That is:

$$C_r(RC) = \sum_i P(RC=i)\ C_r(i)$$

$$K_r(RC) = \sum_i P(RC=i)\ K_r(i)$$

where the summation is over the runway conditions, i, given in Table E1,

$P(RC=i)$ is the proportion of the runway with condition RC=i, and

$C_r(i)$, $K_r(i)$ are the factors for runway condition i for ASD and TOD, respectively, given in Table E1.

Ideally, the runway conditions should be classified into categories and the percentage of time the conditions are in each category and the corresponding adjustment factor would be used in the risk model. However, this is not feasible as there are too many combinations of possible runway conditions. Therefore, the runway condition factors for a particular aircraft were found for each runway condition given in the file for the particular airport over the three year period. Then, weighting the factors by the number of hours for which that runway condition was applicable, the probability distribution of the factors were determined. It was also not feasible, given the available data, to include any interaction between the effects of runway condition and temperature and wind conditions.

An example of the probability distributions of the factor increases in ASD and TOD for the B747 aircraft at Ottawa airport due to runway conditions over the winter months is shown in Figure 5.3.

Runway condition data is not collected on a daily basis during the summer months (April to October) and the distribution of runway conditions therefore had to be estimated using a different approach for these months. Data collected by Environment Canada on the number of hours when precipitation was recorded for each month was used. When rainfall is recorded in a given hour, there will usually be some periods during the hour when rain does not fall. This is offset by the time the runway remains wet after the rainfall ceases. It was assumed that these two periods are roughly equal so that the proportion of time when the runway is wet is equal to the proportion of hours when rainfall occurred.

Standing water (depth > 3 mm or 0.1 in.) only occurs on high quality runways during periods of heavy rainfall. In zero wind and with a crossfall of 1 in 150 (low for runways), a rainfall of approximately 0.75 inches per hour will produce a water depth of nearly 5 mm (0.2 inches) at the center line of a runway 150 feet wide (Herb, AGAR Report 500, Ref 12). Data on the rainfall rate over short periods and frequency and duration of heavy rainfall is not available from Environment Canada. It was therefore assumed that, given rain fell in a given hour, the probability of it being heavy rain was 1/20 and that on average it lasts 1/10 of an hour. Thus, the proportions of time runway is wet or has standing water is estimated by:

$$P(RC=water) = P(Rain\ in\ hour) \times 1/200$$

$$P(RC=wet) = P(Rain\ in\ hour) \times 199/200$$

It was also assumed that, during the summer period, when the runway is wet or has standing water, the whole of the runway is in that condition. These assumptions, although only approximate, should be of the correct order of magnitude and give better estimates of risk than assuming that the runways never have standing water.

E7. Critical Event

Both the type and time of the critical event are modelled in the risk program. Only two types of critical events are considered; events other than engine failure, or engine failure. Critical events other than engine failure are assumed to not affect the ASD and TOD. The effect of variable pilot response times is also considered.

The probability of a critical event on the take-off run is discussed in Section 5.2. It is necessary to determine the probability of a critical event as a function of elapsed time (or distance) from initiation of take-off as the timing of the event affects whether the take-off is aborted or continued and the corresponding accelerate-stop or take-off distance. It is assumed that the take-off will be aborted if the critical event occurs before V_1 and continued if it occurs after V_1.

E7.1 Risk of Critical Event as a Function of Time

The following approach was used to estimate the probability of a critical event as a function of time during the take-off run.

The speed at which the critical events occurred was not reported on the incident reports (refer to Section 2.3) and the distribution of the critical event speed could not be obtained directly from the available data. It therefore was assumed that the times or distances at which critical events occur constitutes a Poisson ("no memory") process. That is, at any time during the take-off run, the probability distribution of the time until a critical event occurs is independent of the time of the last critical event. Since the chance of a critical event on take-off is so low, this is effectively equivalent to the condition that the probability of a critical event is the same at any time on the take-off run.

It is assumed that certain critical events follow a "time-based" Poisson process just described, whereas others follow a "distance-based" Poisson process. The definition of a "distance-base" is obtained by replacing "time" with "distance" in the above definition. (If aircraft travelled at a constant speed during take-off, the two types of processes would be equivalent, but, of course, they do not.)

The time or distance, depending on the type of process, from initiation of the take-off to the critical event will then follow an exponential distribution whose single parameter is either the reciprocal of the mean time or distance between failures, depending on whether a time or distance base is used.

The choice of a time or distance base was determined from the observed number of aborted and continued take-off incident. It is assumed that take-offs were aborted if the critical event occurred before the decision speed, V_1. A typical speed profile for a large jet aircraft during take-off is shown in Figure E3. The times and distances from start of take-off for aircraft to reach V_1, rotation speed V_R and liftoff speed V_{LOF} speeds are given in Table E2.

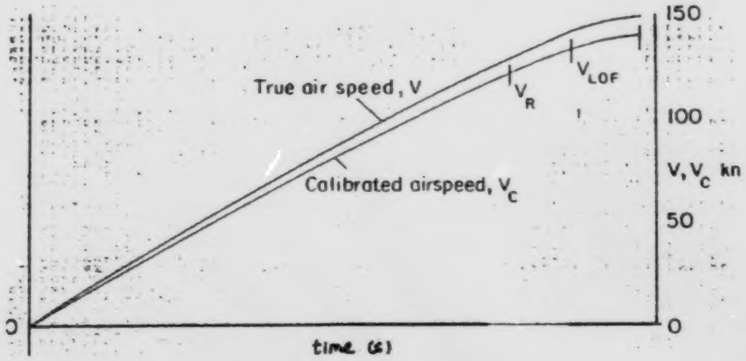


Figure E3 Speed Profile for a Large Jet Aircraft - Weight 123,000 kg, zero wind sea level, 150C

Source: ESDU, Ref. 15

Table E2 Times and Distances to Various Speeds on Take-off for a Large Jet Aircraft

Speed Interval	Ratio V_1/V_R	Distance (m)	Time (s)
0 to V_1	0.85	548	19.0
	0.90	621	20.2
	0.95	700	21.5
	1.00	784	22.9
0 to V_R		784	22.9
0 to V_{LOF}		985	25.8

Source: ESDU, Ref. 15

The times and distances to V_1 depend on the V_1 speed relative to V_R, but the ratio V_1/V_R is generally around 0.9, but can range from 0.8 to 1.0. Thus, the distance to V_1 is about 63% of the distance to liftoff and takes 78% of the time to liftoff. Using these times and distances, the expected percentages of take-offs to abort and continue given a critical event occurs are compared with the observed percentage for jet aircraft in Canada in Table E3.

Table E3 Comparison of Expected and Observed Percentages of Critical Events where Pilot Aborted and Continued Take-off*

Method of determining %		Aborted	Continue
Observed:	Engine Failure	88%	12%
	Other event	53%	47%
Expected % using Base#:	Time	78%	22%
	Distance	63%	37%

* Jet aircraft in Canada, 1986-1989.

# Percentages found assuming probability proportional to base measure (time or distance).

The observed percentage of aborted take-offs due to engine failure (88%) is greater than, but not statistically different from, the expected number using a time base (78%). As the engines operate at a constant power level throughout the take-off run, the probability of engine failure would be expected to be the same during any time interval during take-off. However, engine failures caused by other events such as bird, water or slush ingestion would be expected to occur more often at high speeds. In these cases the probability of engine failure would be more closely related to the distance travelled. The data indicates that these types of engine failure are much less frequent that the power-related types and that time provides a good base for estimating the probability of engine failure. Therefore, it was concluded that engine failures constitute a "time-based" Poisson process so that the time to engine failure on the take-off run can be assumed to follow an exponential distribution.

The distance base appears to be appropriate for estimating the probabilities for non-engine failure critical events. These types of critical events include tire failure, wheel malfunction, instrument or electrical failure, warning light, mechanical and aircraft frame problems, loss of control, risk of collision, severe vibration and birdstrikes. These events can occur at any time, but most are much more likely to occur at high speeds that low speeds. The distance base assumes that the probability of the event occurring at a given time is proportional to the speed at that time. The observed percentage of continued take-offs (47%) is greater than the expected percentage using the distance base (37%), but the difference is not statistically significant.

It therefore was concluded that it would be reasonable to assume that the distance travelled on take-off when a non-engine failure critical event occurs follows also an exponential distribution.

The parameter of the exponential distribution is estimated as follows. The probability of engine failure before time t is

$$P(t_e < t) = 1 - \exp(-u_t t)$$

where u_t is the parameter to be determined and is the reciprocal of the mean time to engine failure on the take-off run.

Setting $t = t_{LOF}$, and using the observed probability of a particular engine failing on take-off from Table 5.7, gives

$$1 - \exp(-u_t t_{LOF}) = 6.3 \times 10^{-6}$$

$$\Rightarrow \quad u_t = \log_e(1 - 6.3 \times 10^{-6}) \,/\, t_{LOF}$$

$$\approx 6.3 \times 10^{-6} \,/\, t_{LOF}$$

Similarly, the probability of a non-engine failure critical event before distance d, using the observed non-engine failure critical event rate on take-off given in Table 5.6, is

$$P(t_e < d\,) = 1 - \exp(-u_d d)$$

and $u_d \approx 2.48 \times 10^{-5} \,/\, d_{LOF}$

where d_{LOF} is the distance to liftoff,

The probability of an aircraft not experiencing an engine failure before time t on the take-off run is equal to the probability that no engines fail before time t which equals

$$[\, P(t_e > t)\,]^{N_e} = \exp(-N_e u_t t)$$

where N_e is the number of engines on the aircraft.

Thus, the probability of a critical event during any time interval, t_1 to t_2, on the take-off run can be estimated by:

For engine failure

$$\begin{aligned} P(t_1 < t_e \le t_2) &= P(t_e > t_1) - P(t_e > t_2) \\ &= \exp(-N_e u_t t_1) - \exp(-N_e u_t t_2) \\ &\approx N_e\, 6.3 \times 10^{-6}\, (t_2 - t_1)/t_{LOF} \end{aligned}$$

For event other than engine failure

$$\begin{aligned} P(t_1 < t_e \le t_2) &= \exp(-u_d d(t_1)) - \exp(u_d d(t_2)) \\ &\approx 2.48 \times 10^{-5}\, (d(t_2) - d(t_1))/d(t_{LOF}) \end{aligned}$$

where t_e is the time of the critical event,
t_{LOF} is the time to liftoff, and
$d(t)$ is the distance travelled by time t.

Several acceleration profiles of aircraft on take-off (B747 and profile given in ESDU, Ref. 15) were examined and the distance travelled was found to be related approximately to the square of the time. This corresponds to a constant acceleration rate of the aircraft during the take-off run. Although the acceleration rate does decrease to some degree during the later part of the acceleration, the assumption of a constant rate is considered to be adequate for this analysis. Thus, for events other than engine failure,

$$P(t_1 < t_e \leq t_2) = 2.48 \times 10^{-5} (t_2^2 - t_1^2)/t_{LOF}^2$$

E7.2 Effect of Critical Event on ASD and TOD

Initially the ASD and TOD were determined for no engine failure. For cases where the critical event is an engine failure, the factors C_e and K_e are introduced, for adjusting the distances. These factors are determined using ASD and TOD values for critical events occurring at V_1 from the AFM for a range of take-off weights.

The TOD, when an engine failure occurs, and the ASD depend on the value of V_1 which can be chosen to suit the particular circumstances of the take-off. A common criteria is to select V_1 so that the field length is balanced; i.e., the ASD equals the TOD. Using this criteria the ratio V_1/V_R is typically in the range 0.85 to 0.95 and varies from take-off to take-off. In the risk model analysis, values of TD and AD were estimated with V_1 chosen so that ASD and TOD are approximately equal for dry runway conditions.

The reduction in ASD due to an engine failure for the B747 and A320 is small and the reduction factor, C_e, does not vary with TOW. However, the factor for the increase in TOD due to an engine failure, K_e, was found to increase with TOW. This is to be expected as an engine failure reduces the maximum power available for acceleration and, the greater the TOW, the lower the acceleration rate and the greater the TOD. Like TOW, other factors such as wind, grade, altitude, temperature and runway conditions also affect the net thrust and the amount of power available to accelerate the aircraft after an engine failure. The effect of these factors can be combined with the effect of TOW using Equation (2) to form an effective TOW. Let %UMTOW* be this effective percentage under MTOW which includes other factors affecting take-off distance.

The effective take-off weight was estimated by first calculating the all engine TOD under the actual conditions, TOD(CE=0). Since %UMTOW* is the percentage under MTOW at standard conditions at which the take-off distance equals the previously calculated TOD(CE=0), from Equation (2):

$$\mathrm{TOD(CE{=}0)} = \mathrm{TOD}_0\ K_w^{\%\mathrm{UMTOW}^*}$$

$$\Rightarrow \quad \%\mathrm{UMTOW}^* = \log[\ \mathrm{TOD(CE{=}0)}/\mathrm{TOD}_0\ ]/\log[K_w]$$

The following relationship was found for the factor increase due to critical event being an engine failure for the A320:

$$K_e = 1.375 - 0.0064\ \%\mathrm{UMTOW}^*$$

If the critical event is not an engine failure, TD is assumed to be unaffected by the critical event. To determine the reduction in TD when the engine failure occurs at speeds after V_1, the acceleration rate was again assumed to be constant before and constant after the engine failure, but the rate less after the failure. It is also assumed that the extra distance on take-off due to the engine failure (TOD(CE=1) - TOD(CE=0)) decreases linearly with the distance travelled between V_1 and when the engine failure occurs. Since the distance travelled is proportional to time squared, the factor increase in TD due to an engine failure at t_e instead of V_1 is calculated by:

$$K_{et} = \{1 + [K_e - 1]\ [1 - (t_e/t_{LOF})^2]/[1 - (t_1/t_{LOF})^2]\}\ /\ K_e \qquad (7)$$

To determine the reduction in AD when a critical event occurs at speeds before V_1, the acceleration rate was again assumed to be constant and the deceleration rate was also assumed to be constant (but not equal to acceleration rate). A 2 second delay between the decision to abort and application of brakes is allowed during which the speed is assumed to equal the event speed. The speed may increase slightly over this time, but this will have little effect on the estimated distance. Thus, for an aborted take-off at speed V_1,

$$AD = \tfrac{1}{2}\ a_0\ t_e^2 + 2 \times 1.686\ V_e + \tfrac{1}{2}\ a_1\ t_d^2$$

where t_d is the deceleration time (s),
a_0 is the acceleration rate (ft/s/s),
a_1 is the deceleration rate (ft/s/s), and
the factor, 1.686, converts knots to ft/s.

Since $t_e = V_e/a_0$ and $t_d = V_e/a_1$,

$$AD = \tfrac{1}{2}\ [\ V_e^2/a_0 + 6.74\ V_e + V_e^2/a_1\ ]$$

Thus, the factor change in AD due to a critical event occurring at V_e rather than V_1 is

$$C_{et} = \frac{V_e^2 \, (1/a_0 + 1/a_1 + 6.74/V_e)}{V_1^2 \, (1/a_0 + 1/a_1 + 6.74/V_1)} \qquad (8)$$

The acceleration and deceleration rates vary with departure characteristics and are not easily determined. However, C_{et} is not sensitive to small variations in these rates and good estimates of C_{et} are found for critical event speeds close to V_1 using the approximation that $C_{et} = V_e^2/V_1^2$. The error is less than 3% when the critical event occurs within 20 knots of the V_1 speed and it is only for speeds in this range that an overshoot accident is likely to occur. The approximation is improved, especially for lower V_e speeds, by assuming fairly typical values of a_0 and a_1 and in Equation (8). The following values were used:

a_0 = 4.0 knots/s
a_1 = 6.5 knots/s

E7.3 Variable Response Time of Pilot

The calculation of ASD in the AFM allows for a 2 second response time by the pilot after the critical event a V_1 before any braking action is undertaken. The response time will in fact vary and depends on the pilot, the chain of events leading up to the critical event and the type of critical event. The 2 second response time is the time allowed by the regulations for the pilot to decide whether to abort the take-off. The actual distribution of the response time is difficult to determine as it is only when a critical event occurs that the reaction time can be determined. These times could be obtained from accident investigation reports, but would be biased if reaction times to critical events not leading to an accident were not also obtained.

Pilot delay aborting take-off was found to be a factor in 30% of abort-crash type accidents (see Table 2.5) and decision times to abort were as long as 6 to 8 seconds in some cases. The risk analysis was used to determine the effect of variable response times on the margin of safety on aborted take-offs. Based on current regulations, accident reports and discussions with pilots, the distribution of response times is assumed to have a mean value of just below 2 seconds, but to have a fairly long tail as shown in Figure E4. The distribution is only approximate, but should give a good indication of the effect on AD of allowing the response time to be variable.

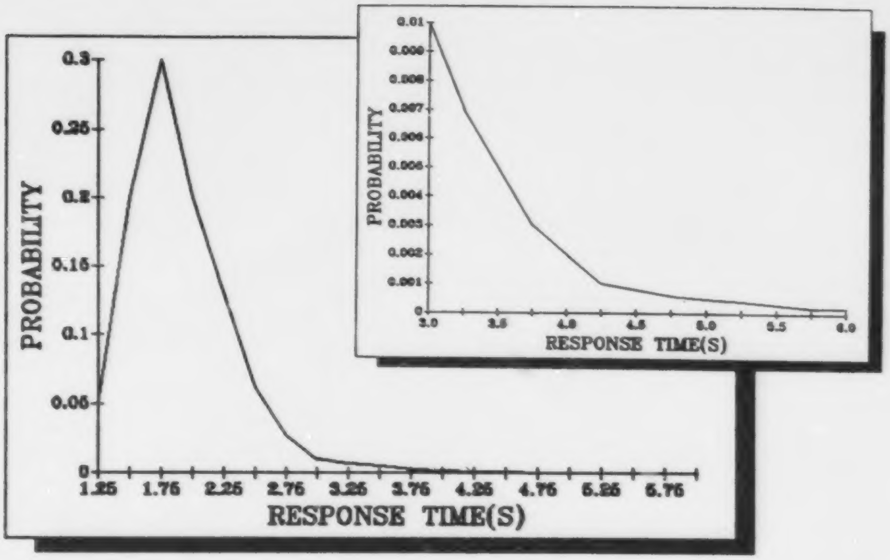


Figure E4 Distribution of the Response Time of Pilot to Critical Event used in Risk Analysis Program

The method of adjusting the AD for different response times is given in Section E2.

E8. Reverse Thrust

Currently reverse thrust has not be included in the calculation of the ASD and maximum take-off weight in Canada and the U.S. (as manufacturers have not elected to demonstrate it meets the requirements of FAR 25.109). However, reverse thrust is often used in aborted take-offs and can be especially effective when wheel braking is poor due to low friction. Therefore, to determine the probability that an actual aborted take-off will result in an accident, the possibility of using reverse thrust and its effect on AD must be considered.

The use of reverse thrust in some situations can reduce the lateral directional stability of the aircraft and thereby increase the chance of the aircraft running off the side of the runway. When an engine failure occurs on a wing engine, use of reverse thrust retards one side of the aircraft more than the other, making it more difficult for the pilot to maintain directional control. A significant crosswind compounds the effect of the engine failure when reverse thrust is used, making it even more difficult for the pilot to keep the aircraft on the runway. Therefore, reverse thrust is assumed to not be used if an engine failure occurs when the crosswind is greater than 5 knots and the crosswind compounds the effect of engine failure.

The effect of reverse thrust was estimated using data on tests conducted by NASA using the B737 (Ref. 52) and data published by Airbus Industrie (Ref. 24) on the A300. The two methods of determining the factor, C_{rev} are given below.

The NASA results show the longitudinal deceleration rates for the B737 on dry, wet and flooded runways with maximum anti-skid braking and the rate when no braking and when only reverse thrust is used. Estimates of the effect of reverse thrust given in Table E4 are found assuming that the deceleration rate with both reverse thrust and maximum anti-skid braking is the sum of two rates. Results are based on tests where approximately 60% of reverse thrust was used. The factor for reduction in ASD due to reverse thrust is calculated using the ASD values calculated for each condition based on typical values of C_r for wet and flooded runway conditions (also given in the table). In calculating the factor it is assumed that the distance travelled during the acceleration and decision time phases of take-off account 70% of the ASD in dry conditions and are unaffected by the runway condition and form of braking used. Reverse thrust is assumed to be only used for two thirds of the deceleration distance since reverse thrust is the last braking device applied.

Table E4 Deceleration Rates with Maximum Anti-skid Braking and Incremental Effect of Reverse Thrust and Reduction Factor in ASD due to Reverse Thrust, Crev

Runway	Rate (g) at 70 knots for:			Increase due	Factor	
Condition	Brakes	Rev.Th.	Total	to Rev.Th.	C_r	C_{rev}
Dry	.49	.11	.60	22%	1.00	0.96
Wet	.32	.11	.43	34%	1.16	0.93
Flooded	.134	.11	.244	82%	1.80	0.81

As shown in the table, the reduction in ASD due to reverse thrust is much greater on contaminated runways. The following expression, derived by regression from the values in Table E4, was used to estimate C_{rev} for a given runway condition for the B737:

$$C_{rev} = 1.13 - 0.17\, C_r \qquad (9)$$

The component of the deceleration rate due to reverse thrust for the B737 can be compared with values of between 0.2 and 0.4 g per engine for a range of jet aircraft given in ESDU (Ref. 15). The upper value in this interval is close to the value for the B737 given in Table E4 of 0.11 g for both engines.

The data on reverse thrust for the A300 gives the maximum take-off weight for fixed runway length and weather conditions for dry and contaminated runways, with and without reverse thrust for an aborted take-off due to engine failure at V_1. The V_1 and V_R speeds are determined for each take-off condition and differ for each case considered. Values are given for a 15 and 35 foot screen height which affect V_1 and V_R when a balance field length is used. Using estimates of the effect of TOW on ASD (i.e. using the factor C_w), the effect of reverse thrust on ASD is calculated. The extra weight that can be carried due to allowance for reverse thrust is converted to an equivalent distance at that TOW and the factor C_{rev} is calculated from the ratio of the extra distance to the ASD distance. The results are summarized in Table E5.

Table E5 Accelerate-stop Distances for the A300 With and Without Reverse Thrust on Contaminated Runways

Runway Conditn, C_r	Screen Height (ft)	No Reverse Thrust		Reverse Thrust		C_{rev}
		%UMTOW	ASDM (ft)	%UMTOW for same ASDM	Equiv. Extra dist Available	
Wet, 1.16	35	8.42	8519	6.68	258	.971
	15	6.03	8878	4.19	285	.969
½"Water, 1.8	35	22.17	6732	17.5	561	.923
	15	22.17	6732	15.33	837	.889
½"Slush, 1.7	35	18.80	7126	15.11	472	.938
	15	16.85	7372	13.26	472	.940
Compact Snow, 1.5	35	6.09	8868	3.37	423	.954
	15	3.70	9242	0.92	443	.954

Using these values of C_{rev} and typical values of C_r (also given in Table E5), the following expression was derived by regression for calculating the effect of reverse thrust after an engine failure on ASD for the A300:

$$C_{rev} = 1.076 - 0.088\ C_r \qquad (10)$$

The effect of reverse thrust with two engines for the B737, Equation (9), is close to double the effect of reverse thrust with one engine for the A300, Equation (10). Therefore, the following equation was used to estimate C_{rev} in the model for the B747 and A320 (the BA146 does not have reverse thrust):

$$C_{rev} = 1 + (0.14 - 0.17\ C_r)\ (N_e-1)/N_e$$

E9. Aircraft, Airport And Runway Characteristics

The aircraft parameters used in the model are the standard ASD and TOD, number of engines, typical values of ratio of V_1 to V_R, V_R and the proportionality factors for adjusting AD and TD for the effect of various characteristics. The values of ASD_0, TOD_0 and V_1/V_R were chosen from the AFM's so that the field length is balanced. The values of these parameters are given in Table E6 for the B747 (Series 100), A320 and BA146 aircraft.

The airport and runway parameters used in the model are the altitude and, for both directions of the main two runways, the direction, gradient, length and the observed distribution of departures by the particular aircraft type on these runways. For Toronto, which has two main parallel runways and another main runway, the average over the two parallel runways of grade, ASDA and TODA are used and these two runways are treated as one in the analysis.

The effect of clearways and stopways were not considered in the analysis as very few runways in Canada have stopways and the determination of allowed take-off weight (ATOW) using clearways is not easily modelled. A portion of the clearway distance can be added to the runway length when determining the ATOW. Thus, for departures at ATOW, allowance for a clearway will permit higher TOW's, but will have little effect on the margin of safety. For departures under ATOW the margin of safety will be increased by the length of clearway available.

Table E6 Aircraft Parameters for Use in the Risk Model

Parameter*		B747-100	A320	BA146
MTOW (lbs)		730,000	162,000	82,250
No. of engines, N_e		4	2	4
Ratio, V_1/V_R (1)		0.96	0.97	0.92
Rotation speed, V_R (1) (knots)		150	140	120
Standard ASD, ASD_0 (ft)		10760	9020	3750
Standard TOD, TOD_0 (ft)		9360	7300	3260
Altitude factor,	ASD - C_a	1.069	1.044	1.060 (6)
	TOD - K_a	1.060	1.065	1.060
Temperature factor,	ASD - C_t	1.0034	1.0050	1.0078 (6)
	TOD - K_t	1.0066	1.0085	1.0078
Grade factor,	ASD - C_g	1.001	1.01 (2)	1.021
	TOD - K_g	1.002	1.03 (2)	1.067
Weight factor,	ASD - C_w	0.974	0.980	0.978 (6)
	TOD - K_w	0.972	0.977	0.978
Head wind factor:	ASD - C_h	0.9952 (3)	0.9934	0.9930
	TOD - K_h	0.9952 (3)	0.9952	0.9941
Tail wind factor:	ASD - C_l	1.014 (3)	1.018	1.0194
	TOD - K_l	1.014 (3)	1.013	1.0210
Engine Failure factor -	C_e	0.98 (4)	0.98 (4)	0.98 (4)
	K_{e0}	1.15 (4)	1.235	1.20 (4)
	K_{e1}	0.0050 (4)	0.0041	0.005 (4)
Reverse Thrust factor -	C_{re0}	1.14 (5)	1.14 (5)	1.0
	C_{re1}	0.17 (5)	0.17 (5)	0.0

* $K_e = K_{e0} - K_{e1}$ %UMTOW (minimum value of $K_e = 1$), and
$C_{rev} = 1 + (C_{re0} - C_{re1}\, C_r)(N_e-1)/N_e$

Notes:
(1) Approximate value, varies with TOW and other take-off conditions.
(2) Based on values for B747 and BA146.
(3) Only one factor determined for adjustment of runway distance available due to head and tail wind which is assumed to be applicable to ASD and TOD.
(4) Estimate based on limited data.
(5) Based on data for A300 and NASA test data for B737.
(6) Same value as for TOD assumed.

E.10 Accuracy Of Model For Estimating ASD And TOD

The values of ASD and TOD calculated from Equations (1) and (2) using parameters given in Table E6 were compared to "observed" values to determine if the model was adequate for use in the risk analysis. "Observed" values were obtained from the UTIAS simulator for the B747 and from the AFM computer program for the A320. Much of this data was also used for estimating the parameters in the model and therefore should lead to mean errors of close to zero and will underestimate the true errors to some extent, especially if the number of parameters is close to the number of data points. However, the comparisons should give an indication of whether the assumptions of independence of characteristics assumed by the model are reasonable.

E10.1 Comparisons Using B747 Aircraft

The UTIAS simulations of the B747 were run with head wind fixed to 10 knots, zero grade and all engines operating in both aborted and continued take-offs. The altitude, temperature, TOW and runway conditions were varied. The "observed" and estimated ASD values are given in Table E7. The errors are less than 5% for most conditions, but are much greater than this when the runway has standing water. The effect of standing water on ASD is greater at high TOW and, by introducing an interaction term between TOW and presence of standing water, these errors are reduced to less than 3%. Excluding the standing water conditions, the average error is 0.3%, the standard deviation of the error is 4.2% and the error is less than 5% in 24 of the 28 (86%) sets of conditions. Ten factor parameters were estimated from the 28 data points.

It should be noted that when the simulation tests were repeated, the observed values were found to vary by up to 3%. Thus, some portion of the errors found using the model may, in part, be due to errors in the "observed" values.

No interaction term between TOW and standing water was included in the model as only one distribution of runway condition factors, including all types of runway conditions, was derived and use of a separate distribution for when there was standing water was not feasible. However, standing water occurs very infrequently and for the purposes of this study use of the simple model should have little effect on the overall estimated accident probabilities.

Table E7 Comparison of "Observed" and Estimated ASD Values Under Various Conditions for the B747*

Temp. (^{0}C)	TOW (lbs)	Runway Cond. #	ASD (ft) "Obs."	Estimate	% Error
Alt.=3500 ft					
27	530,000	Dry μ=0.6	6686	6979	4.4%
		Water μ=0.3	9590	11864	23.7%
-2	530,000	Dry μ=0.6	6035	6316	4.7%
		Slush μ=0.2	9157	9556	4.4%
		Snow μ=0.2	9101	9240	1.5%
		Ice μ=0.1	13466	13074	-2.9%
27	680,000	Dry μ=0.6	12252	11829	-3.5%
		Water μ=0.3	24190	20109	-16.9%
-2	680,000	Dry μ=0.6	11134	10704	-3.9%
		Slush μ=0.2	18198	16196	-11.0%
		Snow μ=0.2	15604	15661	0.4%
		Ice μ=0.1	20217	22159	9.6%
Alt.=500 ft					
27	530,000	Dry μ=0.6	5603	5697	1.7%
		Water μ=0.3	8028	9685	20.6%
-2	530,000	Dry μ=0.6	5026	5156	2.6%
		Dry μ=0.3	6153	6068	-1.4%
		Dry μ=0.2	7530	7352	-2.4%
		Slush μ=0.2	7644	7801	2.0%
		Snow μ=0.2	7734	7543	-2.4%
		Ice μ=0.1	11737	10672	-9.1%
27	680,000	Dry μ=0.6	9825	9656	-1.7%
		Water μ=0.3	19382	16415	-15.3%
-2	680,000	Dry μ=0.6	8970	8738	-2.6%
		Dry μ=0.3	10121	10285	1.6%
		Dry μ=0.2	12154	12461	2.5%
		Slush μ=0.2	12467	13221	6.0%
		Snow μ=0.2	12632	12784	1.2%
		Ice μ=0.1	17350	18088	4.3%

* Zero grade, 10 knot head wind and critical event not engine failure; the ASD was estimated using Equation (1).

# Aircraft braking coefficient, μ, given after condition, "snow" is loose snow, "dry μ=0.3" is similar to wet, and "dry μ=0.2" is similar to compact snow or frost conditions.

Table E8 gives the "observed" and estimated TOD values for the B747 under various conditions. In this case there is no interaction between the TOW and presence of standing water. The average error is 0.1%, the standard deviation is 3.7% and no error is greater than 7%. Seven factor parameters were estimated from the 21 data points.

Table E8 Comparison of "Observed" and Estimated TOD Values Under Various Conditions for the B747*

Alt. (ft)	Temp. (°C)	TOW (lbs)	Runway Cond.	TOD (ft)		
				"Obs."	Estimate	% Error
3500	27	530,000	Dry μ=0.6	7060	6900	-2.3%
			Water μ=0.3	7331	7285	-0.6%
	-2	530,000	Dry μ=0.6	5446	5706	4.8%
			Slush μ=0.2	5989	6400	6.9%
			Snow μ=0.2	6134	6448	5.1%
	27	680,000	Dry μ=0.6	11880	12213	2.8%
			Water μ=0.3	12925	12894	-0.2%
	-2	680,000	Dry μ=0.6	10776	10100	-6.3%
			Slush μ=0.2	11809	11328	-4.1%
			Snow μ=0.2	12052	11414	-5.3%
500	27	530,000	Dry μ=0.6	6018	5798	-3.7%
			Water μ=0.3	6470	6122	-5.4%
	-2	530,000	Dry μ=0.6	4809	4795	-0.3%
			Dry μ=0.2	5058	5015	-0.9%
			Slush μ=0.2	5500	5378	-2.2%
			Snow μ=0.2	5477	5419	-1.1%
	27	680,000	Dry μ=0.6	9941	10263	3.2%
			Water μ=0.3	10172	10836	6.5%
	-2	680,000	Dry μ=0.6	8320	8488	2.0%
			Dry μ=0.2	8805	8876	0.8%
			Slush μ=0.2	9551	9519	-0.3%
			Snow μ=0.2	9446	9591	1.5%

* See notes to Table E7, TOD estimated by Equation (2).

E10.2 Comparisons Using A320 Aircraft

The AFM computer program for the A320 was used to calculate the ASD and TOD under various conditions. Table E9 gives the errors in TOD for various conditions with the following fixed conditions: altitude of 500 feet, temperature of -2°C and zero runway grade. The errors are generally close to zero indicating that the model for estimating TOD for the A320 aircraft works well.

Table E9 Comparison of "Observed" and Estimated TOD Values Under Various Conditions for the A320*

TOW (000 kg)	Head Wind (knt)	Critical Event	V_1/V_R	Runway Cond.	TOD (ft) "Obs."	TOD (ft) Est.	TOD (ft) Error
126	10	Eng.Fail	0.92	½" Slush	7300	7213	-1.2%
133	10	Eng.Fail	0.92	½" Water	7200	7083	-1.6%
144	10	Eng.Fail	0.92	Wet	7200	7237	0.5%
158	10	Eng.Fail	0.92	Comp.Snow	8600	8541	-0.7%
140	-20	Eng.Fail	0.84	¼" Slush	10886	11685	7.3%
140	-10	Eng.Fail	0.84	¼" Slush	10099	9959	-1.4%
120	20	Eng.Fail	0.84	Dry	5048	5071	0.5%
150	20	Eng.Fail	0.84	Dry	8855	8944	1.0%
140	10	Not Eng.F		Dry	5309	5278	-0.6%
150	20	Not Eng.F		Dry	5841	5816	-0.4%
120	30	Not Eng.F		Dry	3537	3583	1.1%

* TOD at altitude of 500 ft, temperature -2^{0}C and zero grade.
When $V_1/V_R = 0.84$, $K_{e0}=1.555$ and $K_{e1}=0.0096$;
when $V_1/V_R = 0.92$, $K_{e0}=1.375$ and $K_{e1}=0.0064$

Errors in the ASD for various take-off weights and runway conditions and the same fixed conditions as above are given in Table E10. The errors are again low indicating that the use of a proportionate change in ASD due to changes in take-off weight and runway conditions works well.

Table E10 Comparison of "Observed" and Estimated ASD Values Under Various Conditions for the A320*

TOW (kg)	Runway Cond.	ASD (ft) "Obs."	ASD (ft) Estimate	ASD (ft) %Error
152,000	¼" Water	11400	11525	1.1%
114,000	½" Water	7300	7460	2.2%
160,000	½" Slush	11400	11569	1.5%
132,000	¼" Slush	8800	8788	-0.1%
146,000	Comp.Snow	9000	8745	-2.8%

* TOD at altitude of 500 ft, temperature -2^{0}C and zero grade, $V_1/V_R = 0.92$

The accuracy of the method for adjusting the TD for when an engine failure occurs after V_1 was tested using the TOD with an engine failure at a different value of the ratio of V_1/V_R. This corresponds to a different time of engine failures. Values of TOD had been found for two values of the ratio, 0.84 and 0.92. The lower of these values was used to set V_1 and the factor for adjusting for the effect of an engine failure, K_e, for this value of the ratio was calculated from the AFM data to be 1.555 at MTOW. The standard TOD (MTOW, no engine failure, zero temperature and altitude and a dry runway) is independent of V_1 and equals 7,300 feet. Assume that $V_R/V_{LOF} = 0.95$, then

$$V_1/V_R = 0.84 \quad \Rightarrow \quad V_1/V_{LOF} = 0.80$$

The adjustment factor for when an engine failure occurs at time t_e after V_1 is given by Equation (7). Using this equation, the estimated effect of an engine failure at $V_e = 0.87\ V_{LOF}$ is found as follows:

$$\begin{aligned} K_{et} &= (1 + 0.555\ (1 - 0.87^2)/(1 - 0.80^2))/1.555 \\ &= 0.884 \end{aligned}$$

Thus, the estimated TOD given an engine failure at 0.87 V_{LOF} is 10,038 feet. Using TOD values from the AFM for $V_1/V_R = 0.92$, which corresponds to $V_1/V_{LOF} = 0.87$ (assuming $V_R/V_{LOF} = 0.95$), the value of TOD under standard conditions for an engine failure at V_1 is 10,015 feet. In this case the error for adjusting for the effect of the time of the critical event is 0.2% of the TOD.

E11. Glossary Of Symbols Used In Risk Analysis

AD	Accelerate-stop distance (for any given runway condition and speed at time of critical event)
AFM	Aircraft Flight Manual
ASD	AD given critical event at V_1, 2 second reaction time, reverse thrust not used and dry runway conditions
ASD_0	Standard ASD at sea level, 0^0C, flat runway, zero head wind, MTOW, dry runway, critical event not engine failure
ASDA	Accelerate-stop distance, including stopway, available
ASDM	Required ASD at MTOW
ATOW	Allowed maximum take-off weight given the runway and environmental conditions

C_a	Proportionate change in ASD due to a 1000 feet increase in altitude
C_e	Proportionate change in ASD due an engine failure at V_1
C_{et}	Proportionate change in ASD due an engine failure at t_e rather than at V_1 ($t_e < V_1$)
C_g	Proportionate change in ASD due to a 1% increase in runway gradient
C_h	Proportionate change in ASD due to a 1 knot increase in head wind (head wind greater than zero)
C_1	Proportionate change in ASD due to a 1 knot increase in tail wind
C_r	Proportionate change in ASD due to runway condition
C_{rev}	Proportionate change in ASD due to use of reverse thrust
C_t	Proportionate change in ASD due to a 1^0C increase in temperature
C_w	Proportionate change in ASD due to a 1% increase in TOW
CE	Critical event (1 for engine failure, 0 otherwise)
CW	Crosswind speed (knots)
d_{LOF}	Distance to liftoff on take-off run
d(t)	Distance travelled on take-off run by time t
DW	Booked/scheduled aircraft take-off weight demand, including fuel, passengers and cargo
HW	Head wind speed (knots)
K_a	Proportionate change in TOD due to a 1000 feet increase in altitude
K_e	Proportionate change in TOD due an engine failure at V_1
K_{et}	Proportionate change in TOD due an engine failure at t_e rather than at V_1 ($t_e > V_1$)
K_g	Proportionate change in TOD due to a 1% increase in runway gradient
K_h	Proportionate change in TOD due to a 1 knot increase in head wind (head wind greater than zero)

K_1	Proportionate change in TOD due to a 1 knot increase in tail wind
K_r	Proportionate change in TOD due to runway condition
K_t	Proportionate change in TOD due to a 1^0C increase in temperature
K_w	Proportionate change in TOD due to a 1% increase in TOW
MTOW	Certified maximum take-off weight of the aircraft (not runway restricted)
Mu (μ)	Braking efficiency coefficient
N_e	Number of engines on aircraft
P(Event)	Probability of event specified in brackets
RC	Runway condition
t_d	Deceleration time of aircraft (s)
t_e	Time of critical event
t_{LOF}	Time to liftoff on take-off run (s)
t_r	Pilot reaction time (s)
TOW	Take-off weight, minimum of ATOW and DW
TD	Take-off distance required to clear a 35 ft screen height (for any given runway condition and speed at time of critical event)
TOD	TD given critical event at V_1 and dry runway conditions
TODA	Take-off distance, including clearway, available
TODM	Required TOD at MTOW
V_1	Speed at which the pilot will abort the take-off if a critical event occurs before that speed or continue take-off if it occurs after that speed.
V_e	Speed at which the critical event occurs
V_R	Speed at which aircraft starts rotation (front wheels lift off ground)
V_{LOF}	Speed at which aircraft lifts off ground

%UATOW	Percentage that TOW is under the allowed take-off weight, ATOW
%UMTOW	Percentage that TOW is under the certified MTOW

Airport: TORONTO INTL   Aircraft type: B747

Departure data based on data for:
Airport: TOR Aircraft: B747 MTOW= 331000 kg, capacity < 125000

Proportion of departures that have:
MTOW which is runway restricted = .79586
actual TOW restricted to ATOW = .00387

Probability Distribution of Margin of Safety (Given Dry Conditions)

Distance	Probability given Critical Event at V1			
Interval	Aircraft at MTOW*		A/C at Actual TOW	
(feet)	ASD	TOD^	ASD	TOD^
0 to 0	.764246	.780097	.000000	.000000
0 to 200	.099776	.047311	.000034	.002967
200 to 400	.035097	.041067	.003224	.001938
400 to 600	.049720	.015401	.001054	.000971
600 to 800	.026299	.047856	.002275	.001260
800 to 1000	.015820	.026518	.002558	.001885
1000 to 1200	.005010	.016263	.003909	.002916
1200 to 1400	.002964	.013075	.005403	.003780
1400 to 1600	.000751	.007512	.007600	.005102
1600 to 1800	.000140	.001973	.010524	.007000
1800 to 2000	.000046	.001918	.013781	.008417
2000 to 2200	.000013	.000656	.018238	.011317
2200 to 2400	.000000	.000160	.023044	.013435
2400 to 2600	.000000	.000054	.027719	.016938
2600 to 2800	.000000	.000019	.033976	.019734
2800 to 3000	.000000	.000003	.039797	.024512
3000 to 3200	.000000	.000000	.045583	.027768
3200 to 3400	.000000	.000000	.050147	.032005
3400 to 3600	.000000	.000000	.054569	.036476
3600 to 3800	.000000	.000000	.056886	.040608
3800 to 4000	.000000	.000000	.058841	.043921
4000 to 8000	.000000	.000000	.540212	.696179
Total			.999373	.999129
Total <1000 ft			.009145	.009020

* MTOW of aircraft (not runway restricted)
^ ASD with no engine failure, TOD with engine failure

Probability Distribution of Extra Runway Available

Extra Rwy Available (feet)	Given Critical Event# at V1			Given a departure (per million deps)*		
	ASD	Rev.T.ASD	TOD	ASD-1	ASD-2	TOD
-5000	.001366	.000121	.000000	.000000	.000088	.000000
-4800	.000194	.000031	.000000	.000762	.000503	.000000
-4600	.000217	.000036	.000000	.000713	.000611	.000000
-4400	.000240	.000044	.000000	.000632	.000749	.000000
-4200	.000260	.000054	.000000	.000822	.000888	.000001
-4000	.000286	.000065	.000000	.001057	.001012	.000002
-3800	.000314	.000078	.000000	.001185	.001146	.000004
-3600	.000349	.000094	.000000	.001337	.001319	.000006
-3400	.000385	.000115	.000000	.001425	.001424	.000007
-3200	.000424	.000136	.000000	.001650	.001620	.000012
-3000	.000470	.000160	.000000	.001875	.001888	.000013
-2800	.000516	.000187	.000000	.002106	.002140	.000021
-2600	.000566	.000216	.000000	.002337	.002379	.000055
-2400	.000629	.000252	.000000	.002700	.002689	.000110
-2200	.000694	.000298	.000000	.003136	.003021	.000158
-2000	.000803	.000350	.000000	.003500	.003391	.000298
-1800	.000959	.000409	.000003	.003993	.003921	.000787
-1600	.001080	.000474	.000010	.004402	.004405	.001309
-1400	.001142	.000574	.000010	.005004	.004976	.001554
-1200	.001288	.000727	.000013	.005775	.005749	.001850
-1000	.001464	.000883	.000022	.006552	.006535	.002155
-800	.001675	.000976	.000029	.007312	.007370	.002846
-600	.001914	.001114	.000149	.008482	.008412	.004247
-400	.002230	.001325	.000277	.009825	.009669	.005212
-200	.002569	.001563	.000578	.011286	.011158	.010129
0	.003408	.001876	.001978	.012889	.013113	.015926
200	.005024	.002395	.002164	.015555	.015596	.014376
400	.005470	.003878	.001426	.019378	.018981	.014814
600	.006220	.004775	.001590	.023211	.022854	.018787
800	.007447	.005277	.002264	.028084	.027459	.026309
1000	.008947	.006472	.003245	.034511	.033097	.032342
1200	.010953	.007940	.004383	.041404	.039889	.043121
1400	.013446	.009980	.005752	.050763	.048608	.053638
1600	.016547	.012518	.007468	.061456	.060000	.063906
1800	.019963	.015716	.009435	.074559	.073929	.082270
2000	.023960	.019437	.011910	.090383	.090955	.099664
2200	.028558	.023670	.014700	.108677	.111501	.117425
2400	.033124	.028383	.017874	.135109	.136086	.138004
2600	.037760	.033478	.021300	.171961	.166942	.159434
2800	.042440	.038766	.025229	.205642	.200527	.180927
3000	.046951	.043842	.029159	.243910	.240343	.208074
3200	.050539	.048379	.033255	.287222	.284443	.234414
3400	.053114	.052248	.037295	.333886	.332995	.255893
3600	.054367	.055181	.041138	.394115	.385809	.277161
3800	.054716	.056897	.044268	.449495	.440205	.291758
4000	.054031	.057458	.046899	.504233	.497401	.302961

Probability Distribution of Extra Runway Available (Continued)

Extra Rwy Available (feet)	Given Critical Event# at V1			Given a departure (per million deps)*		
	ASD	Rev.T.ASD	TOD	ASD-1	ASD-2	TOD
4200	.052525	.056557	.048972	.556780	.554985	.315282
4400	.050113	.054788	.050293	.613341	.611375	.444644
4600	.046838	.052019	.050709	.673092	.675174	.893625
4800	.043300	.049260	.050620	.733783	.743356	2.375579
5000	.207141	.246353	.434150	37.483840	37.514950	.000000
Total	.999093	.997889	.998659	43.429510	43.423900	6.522360

* ASD-1 reaction time=2 sec, ASD-2 variable reaction time

# TOD with engine failure, ASD with all engines operating

Airport: CALGARY INTL Aircraft type: B747

Departure data based on data for:
Airport: CAL Aircraft: B747 MTOW= 331000 kg, capacity < 125000

Proportion of departures that have:
MTOW which is runway restricted = .94363
actual TOW restricted to ATOW = .14507

Probability Distribution of Margin of Safety (Given Dry Conditions)

Distance Interval (feet)	Probability given Critical Event at V1			
	Aircraft at MTOW*		A/C at Actual TOW	
	ASD	TOD^	ASD	TOD^
0 to 0	.947225	.876966	.042239	.000000
0 to 200	.023879	.015197	.103260	.002669
200 to 400	.009632	.035173	.002120	.005661
400 to 600	.010744	.005710	.004441	.002086
600 to 800	.002713	.014813	.005151	.007485
800 to 1000	.003398	.010811	.007392	.122176
1000 to 1200	.001323	.015413	.009970	.005545
1200 to 1400	.000556	.004506	.012702	.009048
1400 to 1600	.000411	.008186	.013716	.006052
1600 to 1800	.000159	.002937	.015567	.007076
1800 to 2000	.000026	.005756	.018941	.008645
2000 to 2200	.000021	.002431	.018300	.012329
2200 to 2400	.000008	.001119	.021883	.013664
2400 to 2600	.000000	.000538	.021193	.016161
2600 to 2800	.000000	.000321	.022169	.017120
2800 to 3000	.000000	.000150	.025489	.019047
3000 to 3200	.000000	.000052	.025066	.018666
3200 to 3400	.000000	.000010	.025793	.021490
3400 to 3600	.000000	.000005	.027405	.020321
3600 to 3800	.000000	.000002	.029751	.022157
3800 to 4000	.000000	.000000	.028527	.022711
4000 to 8000	.000000	.000000	.518701	.639370
Total			.999775	.999480
Total <1000 ft			.164603	.140077

* MTOW of aircraft (not runway restricted)
^ ASD with no engine failure, TOD with engine failure

Probability Distribution of Extra Runway Available

Extra Rwy Available (feet)	Given Critical Event# at V1			Given a departure (per million deps)*		
	ASD	Rev.T.ASD	TOD	ASD-1	ASD-2	TOD
-5000	.000420	.000071	.000000	.000000	.000026	.000000
-4800	.000054	.000015	.000000	.000201	.000136	.000000
-4600	.000055	.000021	.000000	.000141	.000174	.000000
-4400	.000064	.000031	.000000	.000243	.000223	.000000
-4200	.000054	.000036	.000000	.000261	.000237	.000000
-4000	.000088	.000036	.000000	.000275	.000279	.000000
-3800	.000223	.000053	.000000	.000335	.000334	.000000
-3600	.000180	.000067	.000000	.000400	.000399	.000000
-3400	.000087	.000061	.000000	.000505	.000479	.000000
-3200	.000103	.000053	.000000	.000560	.000550	.000000
-3000	.000137	.000073	.000000	.000585	.000588	.000000
-2800	.000135	.000120	.000000	.000640	.000649	.000000
-2600	.000245	.000161	.000000	.000739	.000731	.000008
-2400	.000599	.000191	.000000	.000924	.000899	.000057
-2200	.000571	.000137	.000000	.001162	.001176	.000155
-2000	.000483	.000154	.000000	.001401	.001498	.000239
-1800	.001926	.000378	.000000	.001705	.001984	.000614
-1600	.006988	.000913	.000000	.003844	.003881	.001595
-1400	.004688	.000873	.000000	.006306	.006260	.002524
-1200	.000913	.002745	.000000	.008992	.008144	.004219
-1000	.001063	.006780	.000000	.010354	.009617	.007300
-800	.001328	.003606	.000002	.009327	.010276	.019797
-600	.001652	.001014	.000139	.011126	.011273	.039430
-400	.006271	.001558	.000446	.011895	.014362	.049585
-200	.052804	.008802	.000665	.023606	.027351	.050483
0	.065568	.052659	.003065	.062057	.056475	.066040
200	.014540	.060991	.004793	.096600	.080854	.070625
400	.005754	.014133	.007275	.095939	.095452	.095566
600	.007109	.005254	.026712	.084301	.099529	.252961
800	.009065	.006945	.066332	.107413	.104011	.288399
1000	.011239	.008719	.038463	.121188	.111016	.095069
1200	.013317	.010850	.007807	.122815	.119656	.050435
1400	.015065	.012594	.006714	.118685	.128331	.051758
1600	.017016	.014472	.007561	.138672	.138707	.065666
1800	.018834	.016476	.009562	.159388	.154936	.078623
2000	.020162	.018429	.012167	.168894	.168105	.090545
2200	.021454	.020010	.014313	.189183	.182397	.099583
2400	.022288	.021301	.016100	.207031	.198436	.108495
2600	.023710	.022429	.017261	.221446	.218028	.114505
2800	.024785	.023605	.018722	.236563	.238542	.123045
3000	.025576	.024896	.019705	.255844	.260341	.129044
3200	.026733	.025868	.020516	.285713	.281737	.133066
3400	.027642	.027114	.021023	.311424	.305595	.137851
3600	.028391	.028141	.022036	.331682	.331699	.143652
3800	.028795	.028853	.023009	.355124	.358638	.147302

Probability Distribution of Extra Runway Available (Continued)

Extra Rwy Available (feet)	Given Critical Event# at V1 ASD	Rev.T.ASD	TOD	Given a departure (per million deps)* ASD-1	ASD-2	TOD
4000	.029191	.029375	.023477	.382051	.387183	.153212
4200	.029117	.029752	.024394	.416923	.412659	.157739
4400	.028907	.029853	.025219	.454249	.445483	.287417
4600	.028825	.029908	.025921	.481645	.486603	.878983
4800	.028325	.029941	.026916	.479429	.546771	2.733106
5000	.345661	.375690	.508498	37.407080	37.380890	.000000
Total	.998287	.996043	.998791	43.394490	43.389010	6.523224

* ASD-1 reaction time=2 sec, ASD-2 variable reaction time

# TOD with engine failure, ASD with all engines operating

```
Airport: OTTAWA INTL    Aircraft type: B747

-------------------------------------------------------------------
Departure data based on data for:
Airport:  TOR  Aircraft: B747   MTOW= 331000 kg,  capacity <  125000
-------------------------------------------------------------------
Proportion of departures that have:
 MTOW which is runway restricted =     .99447
 actual TOW restricted to ATOW   =     .02688

Probability Distribution of Margin of Safety (Given Dry Conditions)
-------------------------------------------------------------
   Distance        Probability given Critical Event at V1
   Interval        Aircraft at MTOW*       A/C at Actual TOW
   (feet)             ASD        TOD^         ASD        TOD^
------------------------------------------------------------
     0 to     0   .994472    .962137      .000177    .000000
     0 to   200   .004305    .016860      .023848    .000004
   200 to   400   .000806    .010385      .007211    .002496
   400 to   600   .000254    .005074      .005253    .025287
   600 to   800   .000039    .003052      .009369    .004784
   800 to  1000   .000009    .001755      .015622    .003765
  1000 to  1200   .000000    .000505      .019541    .006384
  1200 to  1400   .000000    .000092      .024177    .011507
  1400 to  1600   .000000    .000022      .028529    .015601
  1600 to  1800   .000000    .000002      .033669    .018676
  1800 to  2000   .000000    .000000      .037702    .022525
  2000 to  2200   .000000    .000000      .042199    .026268
  2200 to  2400   .000000    .000000      .046080    .030131
  2400 to  2600   .000000    .000000      .050768    .033676
  2600 to  2800   .000000    .000000      .053625    .038458
  2800 to  3000   .000000    .000000      .056260    .041739
  3000 to  3200   .000000    .000000      .057101    .044976
  3200 to  3400   .000000    .000000      .056548    .048136
  3400 to  3600   .000000    .000000      .055423    .049708
  3600 to  3800   .000000    .000000      .053158    .051546
  3800 to  4000   .000000    .000000      .050200    .051546
  4000 to  8000   .000000    .000000      .273272    .472395
-------------------------------------------------------------
 Total                                    .999730    .999609
 Total <1000 ft                           .061479    .036336
-------------------------------------------------------------
 * MTOW of aircraft (not runway restricted)
 ^ ASD with no engine failure, TOD with engine failure
```

Probability Distribution of Extra Runway Available

Extra Rwy Available (feet)	Given Critical Event# at V1			Given a departure (per million deps)*		
	ASD	Rev.T.ASD	TOD	ASD-1	ASD-2	TOD
-5000	.001488	.000189	.000000	.000000	.000191	.000000
-4800	.000233	.000051	.000000	.000835	.000555	.000000
-4600	.000254	.000050	.000000	.000859	.000856	.000000
-4400	.000304	.000065	.000000	.001114	.001022	.000000
-4200	.000329	.000081	.000000	.001234	.001172	.000000
-4000	.000369	.000097	.000000	.001409	.001384	.000000
-3800	.000439	.000119	.000000	.001535	.001599	.000000
-3600	.000515	.000150	.000000	.001753	.001788	.000000
-3400	.000514	.000186	.000000	.002187	.002105	.000000
-3200	.000538	.000214	.000000	.002451	.002472	.000000
-3000	.000605	.000260	.000000	.002852	.002780	.000001
-2800	.000687	.000333	.000000	.003196	.003121	.000002
-2600	.000781	.000397	.000000	.003470	.003570	.000003
-2400	.000909	.000463	.000000	.004214	.004127	.000010
-2200	.001008	.000498	.000000	.004679	.004736	.000034
-2000	.001164	.000573	.000000	.005350	.005379	.000057
-1800	.001536	.000709	.000000	.006593	.006267	.000110
-1600	.002474	.000900	.000000	.007584	.007524	.000168
-1400	.002882	.001121	.000003	.009269	.009201	.000459
-1200	.002410	.001534	.000006	.011405	.011135	.001045
-1000	.002613	.002523	.000022	.013165	.012966	.002664
-800	.003132	.002838	.000078	.015498	.014994	.008307
-600	.003874	.002564	.000127	.018336	.017695	.012017
-400	.004776	.002986	.000210	.021327	.021224	.014548
-200	.011015	.004216	.000851	.027172	.027246	.023972
0	.017265	.008598	.002535	.037679	.037592	.039149
200	.013198	.015913	.009226	.049483	.049720	.073652
400	.012644	.014237	.014275	.063098	.060948	.061470
600	.015825	.012477	.006900	.075657	.073165	.039960
800	.020754	.015950	.005142	.089182	.089954	.051941
1000	.024970	.020788	.007903	.109207	.109457	.076337
1200	.028894	.025168	.012315	.135360	.134831	.101838
1400	.032754	.029424	.016336	.169355	.164083	.124031
1600	.036752	.033595	.019739	.205025	.197500	.146165
1800	.040365	.037679	.023503	.242534	.237911	.167431
2000	.043962	.041546	.027317	.282125	.282583	.191257
2200	.047064	.045234	.031010	.334450	.332405	.216091
2400	.049640	.048624	.034932	.396642	.387991	.239616
2600	.051731	.051645	.038722	.453152	.447490	.260854
2800	.052895	.053629	.042108	.512872	.509080	.279210
3000	.052909	.054647	.045401	.578594	.572152	.297031
3200	.051877	.054665	.048244	.648921	.646947	.314056
3400	.049893	.053537	.050131	.720559	.717839	.320221
3600	.047072	.051345	.051188	.787530	.785801	.326454
3800	.043478	.048327	.051639	.854676	.853374	.322435

Probability Distribution of Extra Runway Available (Continued)

Extra Rwy Available (feet)	Given Critical Event# at V1 ASD	Rev.T.ASD	TOD	Given a departure (per million deps)* ASD-1	ASD-2	TOD
4000	.039631	.044508	.051223	.915857	.918588	.315145
4200	.035362	.040107	.049868	1.004913	.983076	.316698
4400	.030833	.035414	.048007	1.072126	1.043654	.305494
4600	.026221	.030634	.045342	1.099397	1.108878	.433117
4800	.022366	.026488	.042495	1.122501	1.160081	1.591188
5000	.066314	.081723	.222576	31.328810	31.381710	.000000
Total	.999625	.999167	.999465	43.452610	43.450080	6.527624

* ASD-1 reaction time=2 sec, ASD-2 variable reaction time
# TOD with engine failure, ASD with all engines operating

```
Airport: HALIFAX INTL    Aircraft type: B747

---------------------------------------------------------------------
Departure data based on data for:
Airport:  TOR  Aircraft: B747   MTOW= 331000 kg,  capacity <  125000
---------------------------------------------------------------------
Proportion of departures that have:
 MTOW which is runway restricted =     .99986
 actual TOW restricted to ATOW   =     .01325

Probability Distribution of Margin of Safety (Given Dry Conditions)
-------------------------------------------------------------
   Distance       Probability given Critical Event at V1
   Interval       Aircraft at MTOW*       A/C at Actual TOW
   (feet)             ASD       TOD^        ASD        TOD^
------------------------------------------------------------
      0 to     0   .999856   .999686     .000009    .000000
      0 to   200   .000006   .000125     .014329    .000000
    200 to   400   .000000   .000035     .003392    .000530
    400 to   600   .000000   .000014     .005461    .013647
    600 to   800   .000000   .000002     .010905    .002922
    800 to  1000   .000000   .000001     .015484    .003228
   1000 to  1200   .000000   .000000     .021636    .006643
   1200 to  1400   .000000   .000000     .027233    .010487
   1400 to  1600   .000000   .000000     .034823    .014700
   1600 to  1800   .000000   .000000     .040843    .019009
   1800 to  2000   .000000   .000000     .049027    .023613
   2000 to  2200   .000000   .000000     .055163    .029179
   2200 to  2400   .000000   .000000     .060634    .035433
   2400 to  2600   .000000   .000000     .064509    .041209
   2600 to  2800   .000000   .000000     .067354    .046570
   2800 to  3000   .000000   .000000     .067786    .051607
   3000 to  3200   .000000   .000000     .065702    .056625
   3200 to  3400   .000000   .000000     .063962    .059551
   3400 to  3600   .000000   .000000     .058800    .061779
   3600 to  3800   .000000   .000000     .052725    .062660
   3800 to  4000   .000000   .000000     .046948    .061422
   4000 to  8000   .000000   .000000     .173071    .398832
-------------------------------------------------------------
 Total                                   .999795    .999647
 Total <1000 ft                          .049578    .020327
-------------------------------------------------------------
 * MTOW of aircraft (not runway restricted)
 ^ ASD with no engine failure, TOD with engine failure
```

Probability Distribution of Extra Runway Available

Extra Rwy Available (feet)	Given Critical Event# at V1			Given a departure (per million deps)*		
	ASD	Rev.T.ASD	TOD	ASD-1	ASD-2	TOD
-5000	.001736	.000126	.000000	.000000	.000228	.000000
-4800	.000348	.000047	.000000	.000988	.000692	.000000
-4600	.000433	.000060	.000000	.001108	.001079	.000000
-4400	.000493	.000078	.000000	.001569	.001378	.000000
-4200	.000572	.000084	.000000	.001640	.001604	.000000
-4000	.000743	.000113	.000000	.001889	.001949	.000000
-3800	.000886	.000143	.000000	.002383	.002388	.000000
-3600	.000986	.000186	.000000	.002975	.002940	.000000
-3400	.001136	.000244	.000000	.003532	.003564	.000000
-3200	.001277	.000302	.000000	.004327	.004231	.000000
-3000	.001472	.000410	.000000	.005002	.004988	.000000
-2800	.001725	.000554	.000000	.006034	.005966	.000000
-2600	.001998	.000717	.000000	.007230	.007151	.000000
-2400	.002319	.000861	.000000	.008233	.008451	.000002
-2200	.002677	.001018	.000000	.010362	.010034	.000012
-2000	.003094	.001247	.000000	.012326	.011932	.000030
-1800	.003588	.001551	.000000	.014041	.014115	.000059
-1600	.004671	.001932	.000000	.017360	.016935	.000128
-1400	.005666	.002388	.000000	.021453	.020456	.000187
-1200	.005825	.003119	.000001	.025295	.024440	.000626
-1000	.006390	.004354	.000013	.030068	.029024	.001320
-800	.007376	.005092	.000055	.034684	.034169	.002980
-600	.008584	.005431	.000101	.040473	.040452	.006939
-400	.009866	.006479	.000197	.047199	.047733	.009653
-200	.014094	.007957	.000602	.056011	.057273	.014436
0	.018610	.012473	.001712	.070867	.070223	.023249
200	.017317	.017131	.004929	.087699	.085184	.041666
400	.019136	.016342	.007469	.104296	.101948	.038747
600	.023575	.018781	.004527	.120734	.120897	.036427
800	.028071	.023717	.005145	.144153	.143612	.053925
1000	.032723	.028918	.008382	.174453	.172791	.077330
1200	.037398	.034226	.012357	.215453	.207489	.103638
1400	.042189	.039684	.016554	.254313	.246840	.129837
1600	.046682	.045088	.021185	.295519	.291895	.160362
1800	.050585	.050261	.026381	.344501	.345028	.196693
2000	.053811	.054487	.031911	.409919	.404291	.229841
2200	.056155	.057823	.037745	.476053	.468824	.266013
2400	.056984	.060184	.043447	.537647	.533057	.299215
2600	.056617	.060941	.048867	.607505	.600041	.328518
2800	.054835	.060125	.053638	.678454	.674821	.355137
3000	.051796	.057929	.057492	.752574	.747756	.374429
3200	.047942	.054356	.060446	.818242	.818049	.388801
3400	.042915	.049634	.061891	.881109	.884524	.391026
3600	.037623	.044125	.061762	.944499	.943764	.380453
3800	.032169	.038227	.060340	1.020203	1.004120	.376098

Probability Distribution of Extra Runway Available (Continued)

Extra Rwy Available (feet)	Given Critical Event# at V1			Given a departure (per million deps)*		
	ASD	Rev.T.ASD	TOD	ASD-1	ASD-2	TOD
4000	.026662	.032210	.057602	1.086947	1.060097	.363038
4200	.021559	.026391	.053643	1.114601	1.109552	.335894
4400	.016870	.020968	.049043	1.131153	1.147577	.303400
4600	.012805	.016065	.043677	1.182337	1.182997	.348366
4800	.009818	.012460	.038564	1.215209	1.222981	.971655
5000	.016890	.022442	.129829	28.434930	28.516070	.000000
Total	.999775	.999585	.999680	43.459140	43.455600	6.529031

* ASD-1 reaction time=2 sec, ASD-2 variable reaction time
# TOD with engine failure, ASD with all engines operating

Airport: TORONTO INTL Aircraft type: A320

Departure data based on data for:
Airport: TOR Aircraft: A310 MTOW= 132000 kg, capacity < 30000

Proportion of departures that have:
MTOW which is runway restricted = .04503
actual TOW restricted to ATOW = .00047

Probability Distribution of Margin of Safety (Given Dry Conditions)

Distance Interval (feet)	Probability given Critical Event at V1 Aircraft at MTOW* ASD	TOD^	A/C at Actual TOW ASD	TOD^
0 to 0	.001686	.052729	.000000	.000000
0 to 200	.003332	.035998	.000000	.000025
200 to 400	.013774	.065044	.000001	.000071
400 to 600	.032179	.152980	.000034	.000209
600 to 800	.041168	.132162	.000119	.000293
800 to 1000	.056923	.115545	.000672	.000456
1000 to 1200	.170648	.124357	.001863	.000570
1200 to 1400	.146591	.046263	.003635	.000657
1400 to 1600	.058192	.031002	.007621	.000895
1600 to 1800	.172341	.029841	.014871	.001203
1800 to 2000	.092847	.043620	.025789	.001600
2000 to 2200	.055675	.033016	.042134	.002182
2200 to 2400	.041657	.043584	.061359	.002803
2400 to 2600	.047814	.034432	.082820	.003818
2600 to 2800	.028543	.021714	.101513	.004844
2800 to 3000	.019029	.011788	.113194	.006485
3000 to 3200	.011645	.015123	.116407	.008192
3200 to 3400	.003182	.006743	.108898	.010258
3400 to 3600	.001922	.002275	.093535	.012951
3600 to 3800	.000563	.001092	.074577	.016117
3800 to 4000	.000150	.000448	.055632	.019448
4000 to 8000	.000035	.000142	.095153	.905884
Total			.999826	.998961
Total <1000 ft			.000826	.001054

* MTOW of aircraft (not runway restricted)
^ ASD with no engine failure, TOD with engine failure

Probability Distribution of Extra Runway Available

Extra Rwy Available (feet)	Given Critical Event# at V1 ASD	Rev.T.ASD	TOD	Given a departure (per million deps)* ASD-1	ASD-2	TOD
-5000	.003288	.000243	.000000	.000000	.000213	.000439
-4800	.000605	.000091	.000000	.001837	.001234	.000087
-4600	.000677	.000112	.000000	.001566	.001477	.000084
-4400	.000757	.000141	.000000	.001777	.001762	.000092
-4200	.000845	.000177	.000000	.001955	.001988	.000094
-4000	.000941	.000218	.000000	.002174	.002383	.000095
-3800	.001048	.000267	.000000	.002847	.002828	.000132
-3600	.001162	.000326	.000000	.003262	.003253	.000148
-3400	.001292	.000396	.000000	.003696	.003737	.000155
-3200	.001434	.000477	.000000	.004205	.004277	.000179
-3000	.001591	.000573	.000000	.004779	.004877	.000193
-2800	.001760	.000687	.000000	.005633	.005557	.000228
-2600	.001943	.000819	.000000	.006612	.006296	.000257
-2400	.002140	.000972	.000000	.007677	.007286	.000245
-2200	.002340	.001147	.000000	.008706	.008239	.000290
-2000	.002550	.001348	.000000	.009105	.009300	.000357
-1800	.002751	.001572	.000000	.010258	.010584	.000422
-1600	.002967	.001821	.000000	.011910	.011782	.000438
-1400	.003162	.002096	.000001	.013408	.013177	.000520
-1200	.003355	.002389	.000001	.014679	.014852	.000585
-1000	.003539	.002709	.000002	.016726	.016482	.000632
-800	.003723	.003039	.000003	.018683	.018277	.000749
-600	.003938	.003387	.000004	.020658	.020508	.000891
-400	.004190	.003760	.000006	.022919	.022396	.000966
-200	.004531	.004153	.000014	.024740	.024661	.001108
0	.005043	.004600	.000036	.027267	.027179	.001441
200	.005813	.005135	.000098	.030213	.030043	.001935
400	.006909	.005827	.000203	.034272	.033833	.002642
600	.008505	.006769	.000332	.038897	.038466	.003277
800	.010901	.008121	.000476	.044590	.043781	.003948
1000	.013985	.010193	.000595	.052635	.051424	.004715
1200	.017876	.013123	.000729	.063020	.061332	.005656
1400	.023357	.017160	.000958	.075627	.073906	.007307
1600	.030855	.022947	.001291	.092025	.090918	.008950
1800	.040883	.031079	.001720	.114292	.114840	.011144
2000	.053735	.042098	.002287	.143297	.146931	.014202
2200	.068183	.055956	.003020	.187585	.189070	.018278
2400	.082718	.071749	.003986	.249940	.240684	.022833
2600	.094120	.087143	.005189	.315285	.303440	.028800
2800	.099007	.098693	.006688	.373881	.372253	.036358
3000	.095905	.103058	.008513	.444532	.443424	.044869
3200	.085103	.098750	.010745	.514895	.510717	.055564
3400	.068664	.086673	.013415	.588905	.569838	.066656
3600	.050617	.069295	.016520	.628673	.617551	.080712
3800	.034404	.050467	.020099	.644132	.651191	.098297

Probability Distribution of Extra Runway Available (Continued)

Extra Rwy Available (feet)	Given Critical Event# at V1			Given a departure (per million deps)*		
	ASD	Rev.T.ASD	TOD	ASD-1	ASD-2	TOD
4000	.021512	.033694	.024095	.670113	.672657	.122439
4200	.012487	.020768	.028564	.692999	.685967	.148199
4400	.006760	.011842	.033151	.700103	.701462	.171456
4600	.003372	.006259	.038095	.711301	.709880	.575884
4800	.001638	.003241	.042020	.715340	.697206	3.640409
5000	.000819	.001824	.734438	24.199680	24.270870	.000000
Total	.999738	.999445	.997216	32.574160	32.568250	4.803867

* ASD-1 reaction time=2 sec, ASD-2 variable reaction time

# TOD with engine failure, ASD with all engines operating

```
Airport: CALGARY INTL    Aircraft type: A320

-------------------------------------------------------------------
Departure data based on data for:
Airport:  CAL  Aircraft: A310   MTOW= 132000 kg,  capacity <   30000
-------------------------------------------------------------------
Proportion of departures that have:
 MTOW which is runway restricted =     .26658
 actual TOW restricted to ATOW   =     .19974

Probability Distribution of Margin of Safety (Given Dry Conditions)
----------------------------------------------------------
   Distance       Probability given Critical Event at V1
   Interval       Aircraft at MTOW*       A/C at Actual TOW
   (feet)              ASD        TOD^        ASD         TOD^
-----------------------------------------------------------
     0 to     0    .240658    .348611     .000010    .000000
     0 to   200    .002624    .071387     .110909    .000034
   200 to   400    .001619    .092567     .063159    .000104
   400 to   600    .001712    .112030     .037249    .000105
   600 to   800    .003977    .060638     .009664    .000142
   800 to  1000    .015666    .072323     .007006    .000190
  1000 to  1200    .050013    .026841     .005325    .000378
  1200 to  1400    .039178    .006433     .003617    .000405
  1400 to  1600    .069525    .019053     .002517    .000874
  1600 to  1800    .086047    .010790     .002394    .001623
  1800 to  2000    .049881    .034732     .002946    .001422
  2000 to  2200    .140854    .011403     .004884    .001984
  2200 to  2400    .049679    .030249     .007953    .002295
  2400 to  2600    .072571    .021530     .012614    .006082
  2600 to  2800    .033204    .013639     .019089    .008310
  2800 to  3000    .047529    .012095     .027883    .004975
  3000 to  3200    .021964    .017768     .038407    .011079
  3200 to  3400    .026965    .010453     .050582    .008529
  3400 to  3600    .017584    .006426     .062948    .012112
  3600 to  3800    .010254    .006291     .072640    .008951
  3800 to  4000    .010171    .008186     .078653    .015506
  4000 to  8000    .008226    .006451     .379150    .913708
------------------------------------------------------------
 Total                                    .999599    .998809
 Total <1000 ft                           .227997    .000575
------------------------------------------------------------
 * MTOW of aircraft (not runway restricted)
 ^ ASD with no engine failure, TOD with engine failure
```

Probability Distribution of Extra Runway Available

Extra Rwy Available (feet)	Given Critical Event# at V1 ASD	Rev.T.ASD	TOD	Given a departure (per million deps)* ASD-1	ASD-2	TOD
-5000	.001886	.000329	.000000	.000000	.000127	.000050
-4800	.000545	.000102	.000000	.001103	.000732	.000012
-4600	.000435	.000100	.000000	.000973	.000855	.000016
-4400	.000422	.000148	.000000	.000899	.001027	.000018
-4200	.000418	.000211	.000000	.001126	.001236	.000020
-4000	.000449	.000252	.000000	.001449	.001390	.000022
-3800	.000497	.000268	.000000	.001574	.001533	.000026
-3600	.000534	.000316	.000000	.001756	.001694	.000033
-3400	.000568	.000427	.000000	.002011	.001952	.000038
-3200	.000612	.000482	.000000	.002200	.002229	.000042
-3000	.000596	.000500	.000000	.002468	.002464	.000052
-2800	.000574	.000520	.000000	.002672	.002677	.000056
-2600	.000727	.000548	.000000	.002903	.002946	.000069
-2400	.001026	.000602	.000000	.003258	.003309	.000093
-2200	.001126	.000639	.000000	.003793	.003739	.000104
-2000	.001253	.000720	.000000	.004417	.004244	.000104
-1800	.001438	.000864	.000000	.005045	.004843	.000132
-1600	.001619	.001073	.000000	.005501	.005524	.000154
-1400	.003165	.001434	.000000	.006231	.006615	.000219
-1200	.007284	.001970	.000000	.008799	.008987	.000243
-1000	.007585	.003399	.000000	.012863	.012134	.000305
-800	.005052	.006627	.000001	.015211	.015164	.000344
-600	.003519	.007338	.000001	.017368	.017496	.000357
-400	.004232	.005774	.000002	.020157	.020124	.000417
-200	.020716	.006810	.000008	.029874	.028129	.000584
0	.070795	.027660	.000048	.056025	.049917	.000874
200	.064497	.066732	.000090	.078804	.081902	.001011
400	.028141	.060774	.000122	.106769	.105099	.001306
600	.012507	.029474	.000171	.124352	.117176	.001786
800	.007517	.010752	.000244	.127495	.124223	.002355
1000	.006490	.007050	.000368	.122304	.127424	.003152
1200	.005879	.005862	.000589	.128587	.130073	.004467
1400	.005959	.005088	.000913	.132942	.135215	.006392
1600	.006815	.005000	.001414	.141022	.140427	.008530
1800	.008469	.005766	.001683	.146323	.145548	.010121
2000	.011125	.007382	.002044	.151749	.149822	.013748
2200	.014825	.010004	.003586	.160533	.156369	.020871
2400	.019618	.013771	.005323	.170761	.170499	.028104
2600	.025597	.018847	.006937	.184849	.186070	.034633
2800	.033023	.025337	.008291	.209670	.208495	.039140
3000	.041647	.033251	.009231	.237149	.236487	.041840
3200	.051121	.042501	.009615	.267474	.267609	.048164
3400	.060351	.052511	.010556	.307141	.309359	.052109
3600	.067604	.062236	.011618	.363218	.357962	.062053
3800	.070964	.069923	.015916	.425553	.411669	.098831

Probability Distribution of Extra Runway Available (Continued)

Extra Rwy Available (feet)	Given Critical Event# at V1			Given a departure (per million deps)*		
	ASD	Rev.T.ASD	TOD	ASD-1	ASD-2	TOD
4000	.069265	.073350	.025582	.480267	.469120	.148318
4200	.062521	.071437	.036107	.525905	.525134	.209102
4400	.052358	.064203	.051385	.566035	.568721	.284759
4600	.041611	.053531	.063133	.602352	.604246	.639679
4800	.032698	.043604	.042878	.654553	.639063	3.401366
5000	.061769	.091422	.687042	25.946060	26.000150	.000000
Total	.999692	.999244	.997008	32.572750	32.567420	4.802866

* ASD-1 reaction time=2 sec, ASD-2 variable reaction time

# TOD with engine failure, ASD with all engines operating

```
Airport: OTTAWA INTL    Aircraft type: A320

-------------------------------------------------------------------
Departure data based on data for:
Airport:  OTT  Aircraft: A310   MTOW= 132000 kg,  capacity <   30000
-------------------------------------------------------------------
Proportion of departures that have:
 MTOW which is runway restricted =     .69844
 actual TOW restricted to ATOW   =     .01157

Probability Distribution of Margin of Safety (Given Dry Conditions)
----------------------------------------------------------
   Distance       Probability given Critical Event at V1
   Interval       Aircraft at MTOW*      A/C at Actual TOW
   (feet)            ASD       TOD^         ASD       TOD^
-----------------------------------------------------------
     0 to     0   .479760   .671271      .000000   .000000
     0 to   200   .118460   .066080      .011562   .000000
   200 to   400   .083682   .022017      .015657   .000000
   400 to   600   .065821   .014125      .031743   .000000
   600 to   800   .053234   .024293      .050649   .000000
   800 to  1000   .048644   .046327      .058540   .000000
  1000 to  1200   .039372   .025902      .053064   .000002
  1200 to  1400   .036230   .031297      .050040   .000006
  1400 to  1600   .032823   .026601      .054910   .000014
  1600 to  1800   .016911   .021620      .064520   .000042
  1800 to  2000   .015560   .020825      .076577   .000136
  2000 to  2200   .005597   .013040      .088121   .000929
  2200 to  2400   .002818   .008237      .093375   .001673
  2400 to  2600   .001012   .004893      .088589   .007702
  2600 to  2800   .000159   .002625      .075463   .002231
  2800 to  3000   .000046   .000863      .060492   .003852
  3000 to  3200   .000012   .000097      .046892   .006580
  3200 to  3400   .000000   .000028      .035023   .010342
  3400 to  3600   .000000   .000001      .023345   .014097
  3600 to  3800   .000000   .000000      .012992   .019340
  3800 to  4000   .000000   .000000      .005851   .026804
  4000 to  8000   .000000   .000000      .002707   .905500
------------------------------------------------------------
 Total                                  1.000111   .999249
 Total <1000 ft                          .168151   .000000
------------------------------------------------------------
 * MTOW of aircraft (not runway restricted)
 ^ ASD with no engine failure, TOD with engine failure
```

Probability Distribution of Extra Runway Available

Extra Rwy Available (feet)	Given Critical Event# at V1 ASD	Rev.T.ASD	TOD	Given a departure (per million deps)* ASD-1	ASD-2	TOD
-5000	.005674	.000626	.000000	.000000	.000727	.000000
-4800	.001044	.000199	.000000	.003171	.002484	.000000
-4600	.001164	.000248	.000000	.003094	.002842	.000000
-4400	.001321	.000327	.000000	.004237	.003684	.000000
-4200	.001483	.000417	.000000	.004095	.004110	.000000
-4000	.001659	.000507	.000000	.004605	.004759	.000000
-3800	.001838	.000625	.000000	.005580	.005703	.000000
-3600	.002044	.000769	.000000	.006892	.006680	.000000
-3400	.002296	.000946	.000000	.007343	.007605	.000000
-3200	.002605	.001131	.000000	.008390	.008555	.000000
-3000	.002928	.001358	.000000	.010326	.009894	.000000
-2800	.003230	.001629	.000000	.012109	.011725	.000000
-2600	.003486	.001950	.000000	.013457	.013451	.000000
-2400	.003719	.002315	.000000	.015621	.015071	.000000
-2200	.003927	.002683	.000000	.017148	.017091	.000000
-2000	.004159	.003055	.000000	.019304	.019313	.000000
-1800	.004410	.003462	.000000	.022246	.021643	.000000
-1600	.004697	.003921	.000000	.024916	.024418	.000000
-1400	.005345	.004430	.000000	.027108	.027266	.000000
-1200	.006293	.004996	.000000	.031273	.030493	.000001
-1000	.007183	.005829	.000000	.034943	.034577	.000001
-800	.008845	.006994	.000000	.040132	.039378	.000001
-600	.010967	.008338	.000000	.046225	.045460	.000002
-400	.012846	.010271	.000000	.053775	.053257	.000003
-200	.016150	.013006	.000000	.062266	.063059	.000004
0	.022155	.017450	.000000	.073945	.076335	.000006
200	.029491	.023866	.000000	.095093	.094359	.000011
400	.042466	.032282	.000000	.123494	.119838	.000021
600	.056678	.045210	.000001	.159324	.155560	.000031
800	.063125	.058605	.000002	.202175	.198567	.000052
1000	.059211	.063426	.000008	.246710	.242718	.000102
1200	.052453	.058924	.000021	.289608	.285837	.000216
1400	.050672	.053190	.000059	.333491	.325987	.000444
1600	.055728	.052834	.000121	.376540	.372016	.000851
1800	.065820	.059081	.000304	.428506	.428193	.002632
2000	.076248	.069825	.000921	.484351	.486219	.008305
2200	.080147	.080007	.003178	.558534	.550732	.022522
2400	.073241	.082702	.005241	.635479	.622592	.022117
2600	.057796	.073975	.003710	.684411	.679764	.017066
2800	.040148	.057116	.004310	.734488	.726311	.026896
3000	.025466	.039125	.007120	.763867	.757684	.042618
3200	.015170	.024617	.010695	.780689	.783015	.060989
3400	.008322	.014413	.014825	.794951	.797351	.083809
3600	.004022	.007659	.020426	.803489	.807979	.113991

Probability Distribution of Extra Runway Available (Continued)

Extra Rwy Available (feet)	Given Critical Event# at V1			Given a departure (per million deps)*		
	ASD	Rev.T.ASD	TOD	ASD-1	ASD-2	TOD
3800	.001644	.003530	.026744	.806183	.808849	.142538
4000	.000549	.001351	.032521	.818680	.812920	.172251
4200	.000144	.000411	.039244	.820455	.817755	.205865
4400	.000029	.000097	.046040	.815121	.824201	.236379
4600	.000004	.000017	.051769	.818613	.825024	.606231
4800	.000001	.000002	.055750	.845639	.827093	3.386489
5000	.000000	.000000	.674873	18.612930	18.680820	.000000
Total	1.000043	.999747	.997774	32.584080	32.580490	4.806557

* ASD-1 reaction time=2 sec, ASD-2 variable reaction time

# TOD with engine failure, ASD with all engines operating

```
Airport: HALIFAX INTL    Aircraft type: A320

--------------------------------------------------------------------------
Departure data based on data for:
Airport:  OTT  Aircraft: A310   MTOW= 132000 kg,  capacity <   30000
--------------------------------------------------------------------------
Proportion of departures that have:
 MTOW which is runway restricted =     .87978
 actual TOW restricted to ATOW   =     .00169

Probability Distribution of Margin of Safety (Given Dry Conditions)
------------------------------------------------------------------
   Distance        Probability given Critical Event at V1
   Interval        Aircraft at MTOW*       A/C at Actual TOW
   (feet)             ASD        TOD^         ASD         TOD^
------------------------------------------------------------------
     0 to     0    .871835    .867259      .000000     .000000
     0 to   200    .026821    .036450      .002697     .000000
   200 to   400    .036514    .036322      .005524     .000000
   400 to   600    .031056    .022386      .015832     .000000
   600 to   800    .015792    .011755      .036305     .000000
   800 to  1000    .012443    .011926      .067112     .000000
  1000 to  1200    .003099    .009836      .100039     .000000
  1200 to  1400    .001949    .002704      .117453     .000000
  1400 to  1600    .000468    .000889      .110794     .000000
  1600 to  1800    .000151    .000509      .100793     .000002
  1800 to  2000    .000056    .000137      .097987     .000012
  2000 to  2200    .000014    .000021      .099710     .000028
  2200 to  2400    .000003    .000005      .096154     .000095
  2400 to  2600    .000000    .000001      .075192     .000206
  2600 to  2800    .000000    .000000      .044663     .000465
  2800 to  3000    .000000    .000000      .020104     .001196
  3000 to  3200    .000000    .000000      .007246     .001604
  3200 to  3400    .000000    .000000      .002007     .001716
  3400 to  3600    .000000    .000000      .000453     .003156
  3600 to  3800    .000000    .000000      .000087     .005083
  3800 to  4000    .000000    .000000      .000014     .007815
  4000 to  8000    .000000    .000000      .000002     .978063
-------------------------------------------------------------------
 Total                                    1.000168     .999440
 Total <1000 ft                            .127470     .000000
-------------------------------------------------------------------
 * MTOW of aircraft (not runway restricted)
 ^ ASD with no engine failure, TOD with engine failure
```

Probability Distribution of Extra Runway Available

Extra Rwy Available (feet)	Given Critical Event# at V1 ASD	Rev.T.ASD	TOD	Given a departure (per million deps)* ASD-1	ASD-2	TOD
-5000	.015765	.001469	.000000	.000000	.002037	.000000
-4800	.003047	.000596	.000000	.010948	.007487	.000000
-4600	.003436	.000734	.000000	.009077	.008092	.000000
-4400	.003984	.000973	.000000	.009803	.010223	.000000
-4200	.004701	.001272	.000000	.011509	.012646	.000000
-4000	.005556	.001573	.000000	.015377	.014866	.000000
-3800	.006552	.001958	.000000	.017753	.017735	.000000
-3600	.007766	.002470	.000000	.021065	.021140	.000000
-3400	.008963	.003157	.000000	.026001	.024984	.000000
-3200	.010277	.003976	.000000	.029507	.029994	.000000
-3000	.011713	.004983	.000000	.037547	.035762	.000000
-2800	.012998	.006170	.000000	.042554	.041510	.000000
-2600	.013885	.007557	.000000	.048374	.048383	.000000
-2400	.014267	.009179	.000000	.056942	.056008	.000000
-2200	.014282	.010810	.000000	.063116	.063778	.000000
-2000	.014200	.012420	.000000	.074005	.072060	.000000
-1800	.014195	.013970	.000000	.081893	.080159	.000000
-1600	.014215	.015421	.000000	.088711	.088297	.000000
-1400	.014032	.016722	.000000	.097469	.096671	.000000
-1200	.013603	.017706	.000000	.107366	.105075	.000000
-1000	.013040	.018263	.000000	.113440	.112381	.000000
-800	.013031	.018525	.000000	.120216	.121550	.000000
-600	.014049	.018712	.000000	.129978	.131622	.000000
-400	.016386	.019272	.000000	.139482	.141836	.000001
-200	.019871	.020612	.000000	.154799	.153106	.000001
0	.023657	.023107	.000000	.173024	.168493	.000001
200	.027087	.026665	.000000	.188899	.187746	.000001
400	.032039	.031176	.000000	.209541	.210077	.000003
600	.042274	.038029	.000000	.241643	.238595	.000007
800	.058917	.049880	.000002	.282163	.279227	.000016
1000	.075449	.066959	.000004	.343407	.333019	.000029
1200	.080024	.081017	.000008	.406719	.397926	.000067
1400	.070473	.081334	.000023	.462180	.462587	.000149
1600	.060008	.070623	.000044	.507593	.511782	.000294
1800	.057332	.062257	.000092	.565695	.561457	.000689
2000	.058314	.060878	.000211	.628449	.619409	.001385
2200	.054649	.060765	.000358	.677175	.672312	.001988
2400	.040916	.053640	.000484	.726674	.717706	.002936
2600	.022461	.036943	.000835	.745620	.742856	.005638
2800	.009023	.018709	.001556	.760696	.761760	.009126
3000	.002778	.006900	.002150	.774336	.774318	.011741
3200	.000686	.001956	.002903	.771967	.777108	.017328
3400	.000138	.000445	.004488	.773873	.776502	.026727
3600	.000022	.000081	.006786	.788754	.783073	.039645

Probability Distribution of Extra Runway Available (Continued)

Extra Rwy Available (feet)	Given Critical Event# at V1 ASD	Rev.T.ASD	TOD	Given a departure (per million deps)* ASD-1	ASD-2	TOD
3800	.000003	.000012	.009932	.789310	.788140	.057574
4000	.000000	.000001	.014299	.788339	.789603	.081598
4200	.000000	.000000	.019896	.778024	.794092	.112073
4400	.000000	.000000	.027114	.799207	.796625	.151192
4600	.000000	.000000	.035975	.811032	.801561	.624799
4800	.000000	.000000	.044488	.800882	.806132	4.092576
5000	.000000	.000000	.826768	16.283250	16.334450	.000000
Total	1.000076	.999878	.998092	32.585150	32.583630	4.808087

* ASD-1 reaction time=2 sec, ASD-2 variable reaction time

# TOD with engine failure, ASD with all engines operating

```
Airport: CALGARY INTL    Aircraft type: A146

----------------------------------------------------------------
Departure data based on data for:
Airport:  CAL  Aircraft: B737   MTOW=  50000 kg,  capacity <   15000
----------------------------------------------------------------
Proportion of departures that have:
 MTOW which is runway restricted =    .00000
 actual TOW restricted to ATOW   =    .00000

Probability Distribution of Margin of Safety (Given Dry Conditions)
-------------------------------------------------------
  Distance        Probability given Critical Event at V1
  Interval        Aircraft at MTOW*       A/C at Actual TOW
  (feet)             ASD        TOD^         ASD        TOD^
---------------------------------------------------------
     0 to     0   .000000    .000000     .000000    .000000
     0 to   200   .000000    .000000     .000000    .000000
   200 to   400   .000000    .000000     .000000    .000000
   400 to   600   .000000    .000000     .000000    .000000
   600 to   800   .000000    .000000     .000000    .000000
   800 to  1000   .000000    .000000     .000000    .000000
  1000 to  1200   .000000    .000000     .000000    .000000
  1200 to  1400   .000000    .000000     .000000    .000000
  1400 to  1600   .000000    .000063     .000000    .000000
  1600 to  1800   .000018    .000846     .000000    .000003
  1800 to  2000   .000081    .001470     .000000    .000007
  2000 to  2200   .001572    .004037     .000007    .000026
  2200 to  2400   .004701    .003277     .000027    .000059
  2400 to  2600   .001418    .031581     .000062    .000240
  2600 to  2800   .032474    .117178     .000274    .000830
  2800 to  3000   .118153    .083100     .000952    .001681
  3000 to  3200   .083107    .053138     .002225    .003645
  3200 to  3400   .050158    .055774     .005413    .007670
  3400 to  3600   .050681    .029793     .012225    .014564
  3600 to  3800   .034117    .027733     .023812    .024774
  3800 to  4000   .030129    .023112     .039532    .037862
  4000 to  8000   .593377    .568888     .913391    .906584
---------------------------------------------------------
 Total                                   .997921    .997946
 Total <1000 ft                          .000000    .000000
---------------------------------------------------------
* MTOW of aircraft (not runway restricted)
^ ASD with no engine failure, TOD with engine failure
```

Probability Distribution of Extra Runway Available

Extra Rwy Available (feet)	Given Critical Event# at V1			Given a departure (per million deps)*		
	ASD	Rev.T.ASD	TOD	ASD-1	ASD-2	TOD
-5000	.000000	.000000	.000000	.000000	.000000	.000000
-4800	.000000	.000000	.000000	.000000	.000000	.000000
-4600	.000000	.000000	.000000	.000000	.000000	.000000
-4400	.000000	.000000	.000000	.000000	.000000	.000000
-4200	.000000	.000000	.000000	.000000	.000000	.000000
-4000	.000000	.000000	.000000	.000000	.000000	.000000
-3800	.000000	.000000	.000000	.000000	.000000	.000000
-3600	.000000	.000000	.000000	.000000	.000000	.000000
-3400	.000000	.000000	.000000	.000000	.000000	.000000
-3200	.000000	.000000	.000000	.000000	.000000	.000000
-3000	.000000	.000000	.000000	.000000	.000000	.000000
-2800	.000000	.000000	.000000	.000000	.000000	.000000
-2600	.000000	.000000	.000000	.000000	.000000	.000000
-2400	.000000	.000000	.000000	.000000	.000000	.000000
-2200	.000000	.000000	.000000	.000000	.000000	.000000
-2000	.000000	.000000	.000000	.000000	.000000	.000000
-1800	.000001	.000001	.000000	.000000	.000000	.000001
-1600	.000001	.000001	.000000	.000001	.000001	.000002
-1400	.000002	.000002	.000000	.000002	.000002	.000005
-1200	.000003	.000003	.000000	.000003	.000003	.000009
-1000	.000005	.000005	.000000	.000005	.000005	.000020
-800	.000008	.000008	.000000	.000008	.000008	.000043
-600	.000012	.000012	.000000	.000013	.000012	.000077
-400	.000018	.000018	.000000	.000022	.000021	.000185
-200	.000026	.000026	.000000	.000034	.000032	.000368
0	.000036	.000036	.000000	.000048	.000048	.000657
200	.000050	.000050	.000000	.000072	.000071	.001148
400	.000068	.000068	.000000	.000107	.000104	.001862
600	.000092	.000092	.000000	.000153	.000150	.003049
800	.000123	.000123	.000000	.000215	.000217	.005089
1000	.000164	.000164	.000000	.000298	.000302	.008180
1200	.000218	.000218	.000000	.000417	.000422	.012377
1400	.000287	.000287	.000001	.000570	.000581	.018574
1600	.000377	.000377	.000003	.000768	.000786	.026519
1800	.000502	.000502	.000012	.001054	.001082	.035268
2000	.000683	.000683	.000031	.001615	.001530	.047041
2200	.000945	.000945	.000097	.002266	.002102	.060393
2400	.001394	.001393	.000334	.002956	.002928	.077538
2600	.002212	.002212	.000870	.004349	.004281	.096488
2800	.003720	.003720	.001931	.006861	.006577	.115483
3000	.006326	.006324	.004133	.010809	.010485	.145577
3200	.010829	.010826	.008311	.017718	.017775	.260332
3400	.018285	.018280	.015384	.030511	.030092	.478661
3600	.029272	.029264	.025628	.052127	.050461	.595316
3800	.042786	.042773	.038323	.083524	.081686	.588702

Probability Distribution of Extra Runway Available (Continued)

Extra Rwy Available (feet)	Given Critical Event# at V1 ASD	Rev.T.ASD	TOD	Given a departure (per million deps)* ASD-1	ASD-2	TOD
4000	.055443	.055427	.050713	.128142	.125335	.676039
4200	.062548	.062529	.059119	.190498	.187494	.724233
4400	.061617	.061597	.061418	.261064	.256242	.626598
4600	.053810	.053791	.057138	.321056	.320964	.986240
4800	.043989	.043972	.049625	.360145	.396112	4.060390
5000	.594226	.587533	.622640	38.828920	38.807200	.000000
Total	.990441	.983626	.996039	40.306030	40.302650	9.268021

* ASD-1 reaction time=2 sec, ASD-2 variable reaction time

# TOD with engine failure, ASD with all engines operating

```
Airport: OTTAWA INTL    Aircraft type: A146

--------------------------------------------------------------------
Departure data based on data for:
Airport:  OTT  Aircraft: B737   MTOW=  50000 kg,  capacity <   15000
--------------------------------------------------------------------
Proportion of departures that have:
 MTOW which is runway restricted =    .00000
 actual TOW restricted to ATOW   =    .00000

Probability Distribution of Margin of Safety (Given Dry Conditions)
-------------------------------------------------------------
   Distance      Probability given Critical Event at V1
   Interval      Aircraft at MTOW*       A/C at Actual TOW
   (feet)           ASD       TOD^         ASD        TOD^
-------------------------------------------------------------
     0 to    0   .000000   .000000      .000000    .000000
     0 to  200   .000000   .000000      .000000    .000000
   200 to  400   .000000   .000000      .000000    .000000
   400 to  600   .000000   .000000      .000000    .000000
   600 to  800   .000000   .000000      .000000    .000000
   800 to 1000   .000000   .000000      .000000    .000000
  1000 to 1200   .000000   .000000      .000000    .000000
  1200 to 1400   .000000   .000000      .000000    .000000
  1400 to 1600   .000000   .000000      .000000    .000000
  1600 to 1800   .000000   .000000      .000000    .000000
  1800 to 2000   .000000   .000000      .000000    .000000
  2000 to 2200   .000000   .000000      .000000    .000000
  2200 to 2400   .000000   .000000      .000000    .000000
  2400 to 2600   .000000   .000135      .000000    .000000
  2600 to 2800   .000000   .001833      .000000    .000004
  2800 to 3000   .000671   .006195      .000002    .000023
  3000 to 3200   .007491   .012975      .000024    .000085
  3200 to 3400   .011285   .048916      .000091    .000246
  3400 to 3600   .043060   .101454      .000304    .000751
  3600 to 3800   .108850   .200968      .001059    .002088
  3800 to 4000   .218425   .106697      .003309    .005040
  4000 to 8000   .610417   .521029      .994364    .990921
-------------------------------------------------------------
 Total                                  .999153    .999159
 Total <1000 ft                         .000000    .000000
-------------------------------------------------------------
 * MTOW of aircraft (not runway restricted)
 ^ ASD with no engine failure, TOD with engine failure
```

Probability Distribution of Extra Runway Available

Extra Rwy Available (feet)	Given Critical Event# at V1			Given a departure (per million deps)*		
	ASD	Rev.T.ASD	TOD	ASD-1	ASD-2	TOD
-5000	.000000	.000000	.000000	.000000	.000000	.000000
-4800	.000000	.000000	.000000	.000000	.000000	.000000
-4600	.000000	.000000	.000000	.000000	.000000	.000000
-4400	.000000	.000000	.000000	.000000	.000000	.000000
-4200	.000000	.000000	.000000	.000000	.000000	.000000
-4000	.000000	.000000	.000000	.000000	.000000	.000000
-3800	.000000	.000000	.000000	.000000	.000000	.000000
-3600	.000000	.000000	.000000	.000000	.000000	.000000
-3400	.000000	.000000	.000000	.000000	.000000	.000000
-3200	.000000	.000000	.000000	.000000	.000000	.000000
-3000	.000000	.000000	.000000	.000000	.000000	.000000
-2800	.000000	.000000	.000000	.000000	.000000	.000000
-2600	.000000	.000000	.000000	.000000	.000000	.000000
-2400	.000000	.000000	.000000	.000000	.000000	.000000
-2200	.000000	.000000	.000000	.000000	.000000	.000000
-2000	.000000	.000000	.000000	.000000	.000000	.000000
-1800	.000000	.000000	.000000	.000000	.000000	.000000
-1600	.000000	.000000	.000000	.000000	.000000	.000000
-1400	.000000	.000000	.000000	.000000	.000000	.000000
-1200	.000000	.000000	.000000	.000000	.000000	.000000
-1000	.000000	.000000	.000000	.000000	.000000	.000000
-800	.000000	.000000	.000000	.000000	.000000	.000000
-600	.000001	.000001	.000000	.000000	.000000	.000000
-400	.000001	.000001	.000000	.000001	.000001	.000000
-200	.000003	.000003	.000000	.000002	.000002	.000000
0	.000005	.000005	.000000	.000005	.000005	.000000
200	.000010	.000010	.000000	.000010	.000010	.000000
400	.000018	.000018	.000000	.000019	.000020	.000000
600	.000030	.000030	.000000	.000039	.000038	.000001
800	.000050	.000050	.000000	.000073	.000069	.000006
1000	.000080	.000080	.000000	.000122	.000120	.000015
1200	.000123	.000123	.000000	.000208	.000206	.000036
1400	.000182	.000182	.000000	.000346	.000337	.000079
1600	.000262	.000262	.000000	.000541	.000532	.000182
1800	.000369	.000369	.000000	.000824	.000809	.000398
2000	.000510	.000510	.000000	.001225	.001207	.000845
2200	.000690	.000690	.000000	.001858	.001845	.001653
2400	.000920	.000920	.000001	.002836	.002711	.003296
2600	.001217	.001217	.000007	.003930	.003789	.005970
2800	.001622	.001622	.000032	.005384	.005349	.011393
3000	.002198	.002198	.000100	.007822	.007653	.021619
3200	.003079	.003079	.000319	.011132	.010904	.037206
3400	.004590	.004589	.000927	.016004	.015939	.062384
3600	.007371	.007369	.002424	.023975	.024299	.108488

Probability Distribution of Extra Runway Available (Continued)

Extra Rwy Available (feet)	Given Critical Event# at V1 ASD	Rev.T.ASD	TOD	Given a departure (per million deps)* ASD-1	ASD-2	TOD
3800	.012510	.012507	.005768	.037384	.038859	.193990
4000	.021760	.021754	.012659	.060586	.064410	.464337
4200	.037361	.037348	.025210	.103507	.108983	.866361
4400	.060261	.060236	.044421	.197124	.192120	1.075109
4600	.087122	.087084	.068659	.339812	.337605	1.626149
4800	.107930	.107886	.090269	.493327	.548352	5.263113
5000	.643173	.637365	.746830	39.111510	39.052650	.000000
Total	.993011	.987070	.997009	40.410590	40.406990	9.277051

* ASD-1 reaction time=2 sec, ASD-2 variable reaction time

# TOD with engine failure, ASD with all engines operating

```
Airport: HALIFAX INTL    Aircraft type: A146

------------------------------------------------------------------
Departure data based on data for:
Airport:  HAL  Aircraft: B737   MTOW=  50000 kg,  capacity <   15000
------------------------------------------------------------------
Proportion of departures that have:
 MTOW which is runway restricted =     .00000
 actual TOW restricted to ATOW   =     .00000

Probability Distribution of Margin of Safety (Given Dry Conditions)
-----------------------------------------------------------
   Distance       Probability given Critical Event at V1
   Interval       Aircraft at MTOW*      A/C at Actual TOW
   (feet)            ASD       TOD^         ASD        TOD^
-----------------------------------------------------------
     0 to     0   .000000   .000000      .000000   .000000
     0 to   200   .000000   .000000      .000000   .000000
   200 to   400   .000000   .000000      .000000   .000000
   400 to   600   .000000   .000000      .000000   .000000
   600 to   800   .000000   .000000      .000000   .000000
   800 to  1000   .000000   .000000      .000000   .000000
  1000 to  1200   .000000   .000000      .000000   .000000
  1200 to  1400   .000000   .000000      .000000   .000000
  1400 to  1600   .000000   .000000      .000000   .000000
  1600 to  1800   .000000   .000000      .000000   .000000
  1800 to  2000   .000000   .000000      .000000   .000000
  2000 to  2200   .000000   .000000      .000000   .000000
  2200 to  2400   .000000   .000000      .000000   .000000
  2400 to  2600   .000006   .000121      .000000   .000001
  2600 to  2800   .000141   .002369      .000002   .000029
  2800 to  3000   .000505   .001678      .000009   .000037
  3000 to  3200   .002994   .001259      .000054   .000092
  3200 to  3400   .011918   .106061      .000230   .001113
  3400 to  3600   .032908   .114871      .000758   .002457
  3600 to  3800   .223125   .111536      .003613   .005989
  3800 to  4000   .072933   .046324      .008874   .013243
  4000 to  8000   .655264   .615576      .985384   .975984
-----------------------------------------------------------
 Total                                   .998925   .998945
 Total <1000 ft                          .000000   .000000
-----------------------------------------------------------
 * MTOW of aircraft (not runway restricted)
 ^ ASD with no engine failure, TOD with engine failure
```

Probability Distribution of Extra Runway Available

Extra Rwy Available (feet)	Given Critical Event# at V1			Given a departure (per million deps)*		
	ASD	Rev.T.ASD	TOD	ASD-1	ASD-2	TOD
-5000	.000000	.000000	.000000	.000000	.000000	.000000
-4800	.000000	.000000	.000000	.000000	.000000	.000000
-4600	.000000	.000000	.000000	.000000	.000000	.000000
-4400	.000000	.000000	.000000	.000000	.000000	.000000
-4200	.000000	.000000	.000000	.000000	.000000	.000000
-4000	.000000	.000000	.000000	.000000	.000000	.000000
-3800	.000000	.000000	.000000	.000000	.000000	.000000
-3600	.000000	.000000	.000000	.000000	.000000	.000000
-3400	.000000	.000000	.000000	.000000	.000000	.000000
-3200	.000000	.000000	.000000	.000000	.000000	.000000
-3000	.000000	.000000	.000000	.000000	.000000	.000000
-2800	.000000	.000000	.000000	.000000	.000000	.000000
-2600	.000000	.000000	.000000	.000000	.000000	.000000
-2400	.000000	.000000	.000000	.000000	.000000	.000000
-2200	.000000	.000000	.000000	.000000	.000000	.000000
-2000	.000000	.000000	.000000	.000000	.000000	.000000
-1800	.000000	.000000	.000000	.000000	.000000	.000000
-1600	.000000	.000000	.000000	.000000	.000000	.000000
-1400	.000000	.000000	.000000	.000000	.000000	.000000
-1200	.000000	.000000	.000000	.000000	.000000	.000000
-1000	.000000	.000000	.000000	.000000	.000000	.000000
-800	.000000	.000000	.000000	.000000	.000000	.000000
-600	.000001	.000001	.000000	.000000	.000000	.000000
-400	.000002	.000002	.000000	.000001	.000001	.000000
-200	.000004	.000004	.000000	.000003	.000003	.000000
0	.000009	.000009	.000000	.000007	.000007	.000000
200	.000018	.000018	.000000	.000017	.000016	.000000
400	.000036	.000036	.000000	.000040	.000037	.000000
600	.000069	.000069	.000000	.000081	.000077	.000004
800	.000127	.000127	.000000	.000158	.000156	.000012
1000	.000221	.000221	.000000	.000302	.000304	.000024
1200	.000367	.000367	.000000	.000570	.000556	.000042
1400	.000585	.000585	.000000	.000995	.000971	.000130
1600	.000907	.000907	.000000	.001644	.001621	.000402
1800	.001366	.001366	.000000	.002727	.002694	.000892
2000	.002007	.002007	.000000	.004673	.004516	.001803
2200	.002903	.002903	.000000	.007381	.007018	.003662
2400	.004133	.004133	.000005	.010930	.010663	.007164
2600	.005779	.005778	.000027	.016789	.016362	.012982
2800	.007969	.007967	.000060	.025442	.024728	.022320
3000	.010829	.010827	.000337	.036781	.035905	.042376
3200	.014620	.014616	.001234	.053190	.052392	.069437
3400	.020047	.020041	.003053	.076701	.076851	.112700
3600	.027799	.027791	.007116	.108377	.111264	.181911

Probability Distribution of Extra Runway Available (Continued)

Extra Rwy Available (feet)	Given Critical Event# at V1			Given a departure (per million deps)*		
	ASD	Rev.T.ASD	TOD	ASD-1	ASD-2	TOD
3800	.038405	.038393	.015180	.154088	.158386	.280514
4000	.053272	.053254	.028533	.223116	.226272	.447089
4200	.071226	.071197	.046382	.349033	.332631	.854353
4400	.086739	.086703	.065335	.500537	.472211	1.211000
4600	.092930	.092893	.080620	.635413	.646109	1.649907
4800	.090203	.090165	.089674	.767960	.844407	4.774554
5000	.464762	.462662	.660181	37.622820	37.574350	.000000
Total	.997583	.995288	.997535	40.596650	40.593620	9.281940

* ASD-1 reaction time=2 sec, ASD-2 variable reaction time

# TOD with engine failure, ASD with all engines operating

```
Airport: PRINCE GEORGE    Aircraft type: A146

-----------------------------------------------------------------------
Departure data based on data for:
Airport:  PRG  Aircraft: B737   MTOW=  50000 kg,  capacity <   15000
-----------------------------------------------------------------------
Proportion of departures that have:
 MTOW which is runway restricted =     .00046
 actual TOW restricted to ATOW   =     .00000

Probability Distribution of Margin of Safety (Given Dry Conditions)
------------------------------------------------------------
   Distance       Probability given Critical Event at V1
   Interval       Aircraft at MTOW*        A/C at Actual TOW
   (feet)            ASD        TOD^         ASD        TOD^
-------------------------------------------------------------
     0 to     0   .000014    .000724     .000000    .000000
     0 to   200   .000113    .003223     .000000    .000006
   200 to   400   .000225    .010820     .000000    .000023
   400 to   600   .002174    .024719     .000004    .000075
   600 to   800   .012520    .052481     .000026    .000262
   800 to  1000   .009491    .010613     .000083    .000583
  1000 to  1200   .068205    .018782     .000405    .001397
  1200 to  1400   .027114    .019943     .001122    .002808
  1400 to  1600   .008916    .008019     .002894    .005119
  1600 to  1800   .017328    .006779     .006171    .008206
  1800 to  2000   .008818    .008049     .011080    .012270
  2000 to  2200   .009089    .042633     .017614    .017133
  2200 to  2400   .006540    .075148     .024918    .022657
  2400 to  2600   .111369    .148324     .030416    .026427
  2600 to  2800   .248669    .212876     .028842    .025988
  2800 to  3000   .170037    .116694     .022144    .023256
  3000 to  3200   .074763    .066071     .019520    .022315
  3200 to  3400   .072814    .079090     .025741    .026495
  3400 to  3600   .055691    .044227     .041660    .038293
  3600 to  3800   .058005    .029737     .067372    .056671
  3800 to  4000   .021594    .015255     .100301    .080906
  4000 to  8000   .016712    .005996     .599562    .628956
--------------------------------------------------------------
 Total                                   .999875    .999847
 Total <1000 ft                          .000113    .000948
--------------------------------------------------------------
 * MTOW of aircraft (not runway restricted)
 ^ ASD with no engine failure, TOD with engine failure
```

Probability Distribution of Extra Runway Available

Extra Rwy Available (feet)	Given Critical Event# at V1			Given a departure (per million deps)*		
	ASD	Rev.T.ASD	TOD	ASD-1	ASD-2	TOD
-5000	.000000	.000000	.000000	.000000	.000000	.000007
-4800	.000000	.000000	.000000	.000000	.000000	.000002
-4600	.000000	.000000	.000000	.000000	.000000	.000002
-4400	.000000	.000000	.000000	.000000	.000000	.000002
-4200	.000000	.000000	.000000	.000000	.000000	.000003
-4000	.000001	.000001	.000000	.000000	.000000	.000003
-3800	.000001	.000001	.000000	.000001	.000001	.000004
-3600	.000002	.000002	.000000	.000002	.000002	.000005
-3400	.000003	.000003	.000000	.000003	.000003	.000006
-3200	.000006	.000006	.000000	.000005	.000005	.000007
-3000	.000009	.000009	.000000	.000009	.000009	.000009
-2800	.000013	.000013	.000000	.000016	.000015	.000010
-2600	.000019	.000019	.000000	.000025	.000025	.000015
-2400	.000028	.000028	.000001	.000038	.000039	.000021
-2200	.000040	.000040	.000001	.000058	.000060	.000032
-2000	.000054	.000054	.000001	.000086	.000089	.000049
-1800	.000076	.000076	.000001	.000125	.000129	.000084
-1600	.000105	.000105	.000002	.000193	.000191	.000157
-1400	.000145	.000145	.000002	.000310	.000286	.000277
-1200	.000201	.000201	.000002	.000428	.000401	.000478
-1000	.000276	.000276	.000003	.000575	.000571	.000805
-800	.000373	.000373	.000004	.000836	.000827	.001352
-600	.000499	.000499	.000005	.001214	.001177	.002167
-400	.000664	.000664	.000006	.001660	.001632	.003674
-200	.000870	.000870	.000010	.002304	.002302	.005373
0	.001131	.001131	.000022	.003214	.003175	.007966
200	.001480	.001480	.000053	.004416	.004339	.011928
400	.001916	.001916	.000146	.005988	.005857	.017493
600	.002491	.002491	.000354	.007918	.007831	.024110
800	.003343	.003343	.000783	.011036	.010965	.035830
1000	.004581	.004580	.001673	.015844	.015284	.048727
1200	.006417	.006416	.003208	.021433	.020826	.068592
1400	.009205	.009203	.005561	.029762	.029227	.098106
1600	.013263	.013259	.008787	.043884	.042728	.124402
1800	.018491	.018485	.012847	.063474	.061912	.152813
2000	.024345	.024337	.017731	.090700	.088895	.185531
2200	.030214	.030203	.022741	.126718	.125621	.211555
2400	.034144	.034130	.025914	.169024	.169179	.226093
2600	.033775	.033761	.025676	.215047	.217044	.225205
2800	.031567	.031556	.023525	.261982	.264412	.232325
3000	.033852	.033840	.023311	.324855	.318075	.281187
3200	.044264	.044247	.028451	.402611	.386859	.370567
3400	.062001	.061979	.040829	.493580	.486051	.521830
3600	.084366	.084339	.059795	.630348	.628143	.717109

Probability Distribution of Extra Runway Available (Continued)

Extra Rwy Available (feet)	Given Critical Event# at V1 ASD	Rev.T.ASD	TOD	Given a departure (per million deps)* ASD-1	ASD-2	TOD
3800	.107524	.107495	.084010	.833469	.820490	.931981
4000	.124788	.124754	.110723	1.086946	1.074111	1.106488
4200	.123796	.123763	.130956	1.364252	1.346672	1.146449
4400	.096436	.096412	.130720	1.631366	1.605606	1.013569
4600	.057849	.057837	.106394	1.815269	1.799350	.796582
4800	.030672	.030667	.075727	1.960828	1.910595	.742701
5000	.014100	.014093	.059068	29.083040	29.243040	.000000
Total	.999953	.999658	1.000065	40.693190	40.691230	9.305481

* ASD-1 reaction time=2 sec, ASD-2 variable reaction time

# TOD with engine failure, ASD with all engines operating

Airport: EDMONTON MUNICIPAL   Aircraft type: A146

Departure data based on data for:
Airport: EDM Aircraft: B737 MTOW= 50000 kg, capacity < 15000

Proportion of departures that have:
MTOW which is runway restricted = .00000
actual TOW restricted to ATOW = .00000

Probability Distribution of Margin of Safety (Given Dry Conditions)

Distance Interval (feet)	Probability given Critical Event at V1 Aircraft at MTOW* ASD	TOD^	A/C at Actual TOW ASD	TOD^
0 to 0	.000004	.000732	.000000	.000000
0 to 200	.000152	.003104	.000000	.000001
200 to 400	.002422	.008543	.000000	.000005
400 to 600	.004889	.008011	.000004	.000024
600 to 800	.009529	.092574	.000023	.000219
800 to 1000	.062294	.226041	.000163	.000723
1000 to 1200	.190958	.195960	.000757	.001821
1200 to 1400	.244970	.138906	.002391	.004475
1400 to 1600	.135382	.085909	.006699	.010171
1600 to 1800	.102478	.078763	.017039	.021231
1800 to 2000	.087957	.085173	.037695	.040209
2000 to 2200	.074517	.046756	.072016	.069061
2200 to 2400	.060730	.021487	.117232	.104888
2400 to 2600	.017405	.007242	.160239	.141393
2600 to 2800	.005568	.000593	.180118	.163473
2800 to 3000	.000529	.000007	.165064	.159744
3000 to 3200	.000017	.000000	.120947	.129413
3200 to 3400	.000000	.000000	.071873	.084909
3400 to 3600	.000000	.000000	.033606	.044564
3600 to 3800	.000000	.000000	.011227	.017682
3800 to 4000	.000000	.000000	.002367	.004860
4000 to 8000	.000000	.000000	.000249	.000853
Total			.999710	.999719
Total <1000 ft			.000191	.000973

* MTOW of aircraft (not runway restricted)
^ ASD with no engine failure, TOD with engine failure

Probability Distribution of Extra Runway Available

Extra Rwy Available (feet)	Given Critical Event# at V1			Given a departure (per million deps)*		
	ASD	Rev.T.ASD	TOD	ASD-1	ASD-2	TOD
-5000	.000000	.000000	.000000	.000000	.000000	.000000
-4800	.000000	.000000	.000000	.000000	.000000	.000000
-4600	.000000	.000000	.000000	.000000	.000000	.000000
-4400	.000001	.000001	.000000	.000000	.000000	.000000
-4200	.000001	.000001	.000000	.000001	.000001	.000000
-4000	.000002	.000002	.000000	.000001	.000001	.000000
-3800	.000005	.000005	.000000	.000003	.000003	.000000
-3600	.000007	.000007	.000000	.000006	.000007	.000000
-3400	.000012	.000012	.000000	.000012	.000013	.000000
-3200	.000020	.000020	.000000	.000021	.000022	.000000
-3000	.000033	.000033	.000000	.000037	.000039	.000000
-2800	.000054	.000054	.000000	.000072	.000069	.000000
-2600	.000084	.000084	.000000	.000128	.000117	.000000
-2400	.000124	.000124	.000000	.000195	.000188	.000000
-2200	.000181	.000181	.000000	.000302	.000302	.000000
-2000	.000258	.000258	.000000	.000493	.000475	.000000
-1800	.000360	.000360	.000000	.000749	.000719	.000001
-1600	.000495	.000495	.000000	.001083	.001079	.000003
-1400	.000669	.000669	.000000	.001593	.001575	.000007
-1200	.000889	.000889	.000000	.002309	.002261	.000023
-1000	.001160	.001160	.000000	.003214	.003171	.000070
-800	.001482	.001482	.000000	.004426	.004345	.000192
-600	.001856	.001856	.000000	.006061	.006018	.000453
-400	.002288	.002288	.000000	.008473	.008325	.000995
-200	.002736	.002736	.000000	.011333	.010870	.001917
0	.003230	.003230	.000003	.014250	.014064	.003695
200	.003791	.003790	.000013	.018264	.018127	.007271
400	.004437	.004437	.000072	.023535	.023045	.014234
600	.005293	.005292	.000291	.029744	.029348	.026502
800	.006586	.006585	.000891	.037411	.037371	.047303
1000	.008774	.008772	.002223	.047550	.048149	.086934
1200	.012621	.012619	.005193	.062208	.063849	.153438
1400	.019682	.019677	.011460	.083909	.087510	.254628
1600	.032370	.032362	.023172	.128028	.129171	.414589
1800	.053381	.053367	.042695	.214961	.204739	.640751
2000	.083840	.083816	.071317	.340946	.327881	.900021
2200	.119158	.119120	.106371	.531228	.518005	1.171630
2400	.148211	.148158	.139922	.793448	.777499	1.346840
2600	.156434	.156376	.159426	1.103647	1.086890	1.361476
2800	.136665	.136618	.154848	1.428591	1.399293	1.167956
3000	.097487	.097457	.125891	1.667958	1.653801	.840733
3200	.056553	.056537	.084059	1.849866	1.840696	.503889
3400	.026288	.026281	.045336	1.956371	1.960266	.240135
3600	.009330	.009328	.019115	2.043406	2.035148	.088482

Probability Distribution of Extra Runway Available (Continued)

Extra Rwy Available (feet)	Given Critical Event# at V1			Given a departure (per million deps)*		
	ASD	Rev.T.ASD	TOD	ASD-1	ASD-2	TOD
3800	.002317	.002316	.005940	2.062432	2.084443	.023068
4000	.000353	.000353	.001237	2.128689	2.125014	.003854
4200	.000026	.000026	.000149	2.199141	2.180737	.000350
4400	.000001	.000001	.000008	2.241886	2.244706	.000009
4600	.000000	.000000	.000000	2.312600	2.327085	.000000
4800	.000000	.000000	.000000	2.434478	2.426073	.000000
5000	.000000	.000000	.000000	14.902550	14.998510	.000000
Total	.999544	.999235	.999631	40.676600	40.675530	9.301451

* ASD-1 reaction time=2 sec, ASD-2 variable reaction time

# TOD with engine failure, ASD with all engines operating

APPENDIX F

ANALYSIS OF RUNWAY CONDITION REPORTS

Runway conditions reports were obtained for the last three years from Ottawa, Halifax, Edmonton and Calgary International airports and from Prince George airport. A sample of the standard report form used for recording runway conditions is given below (Ottawa uses a slightly different form). Runway conditions for the main runway at each of the five airports were entered into a computerized database and analyzed. The time interval between reports was calculated and used as the time period for which each report was applicable. Checks were made or input errors and any inconsistencies in the data.

The quality of the data varied considerably between airports. At some airports it appears that reports were not always filed when conditions changed, especially when conditions changed from contaminated to bare and dry. It was therefore necessary to make some assumptions on the periods for which the runway remained contaminated, based on data from other airports. In addition, in some years reporting commenced in mid-November and/or ceased in mid-March at some airports, presumeably because no snow fall was recorded in those periods. As data for the full month was required to obtain frequency distributions of runway conditions for each month, records were added based on average weather data for that month assuming no snow falls occurred.

A number of tables summarizing the runway conditions were produced for each runway, but the more detailed tables were only produced when the data was of good enough quality to give meaningful results. The tables produced were:

1. Average percentage of time a section of the runway is in each condition by month.

2. Pecentage distribution of each runway condition by month.

3. Average percentage of time a section of the runway is in each condition given a specified range of % ice cover.

4. Distribution of Tapley readings by month for each condition.

5. Distribution of Depth readings by month for each condition.

Table 1 provides a quick overall view of the distribution of runway conditions in each month. However, from this table it is not possible to determine what proportion of the runway at any given time is in each condition and how the various conditions occur in combination with eachother.

Table 2 indicates how often the percentage of the runway is in a particular condition. For example it gives the percentage of time when none of the runway is bare and dry.

Table 3 indicates what are other common runway conditions when various percentages of the runway are ice covered.

Tables 4 and 5 show the typical Tapley brake efficiency values and depth of contaminant for each type of contaminant when the runway condition is classified as either more or less than 50% of that type of contaminant.

Tables 2 and 3 were not produced for Edmonton and Calgary was the data quality was not sufficient.

Transport Canada Transports Canada

APPENDIX D ANNEXE D
AK-72-40-[illegible]
ISSUE 7 EDITION 7

AIRPORTS AND CONSTRUCTION SERVICES DIRECTORATE
AIRCRAFT MOVEMENT SURFACE CONDITION REPORT AND JAMES BRAKE/TAPLEY READING

DIRECTION GÉNÉRALE DES SERVICES DES AÉROPORTS ET DE LA CONSTRUCTION
COMPTE-RENDU DE L'ÉTAT DES AIRES DE MOUVEMENT POUR AÉRONEFS ET RELEVÉ D'INDICE DE FREINAGE AU DÉCÉLÉROMÈTRE JAMES/TAPLEY

AIRPORT - AÉROPORT

REPORT NO. - COMPTE RENDU N°

SURFACE CONDITION DATA - RENSEIGNEMENTS SUR L'ÉTAT DE SURFACE

RUNWAY PISTE	PORTION PARTIE	[illegible] FEET PIEDS	BARE & DRY %	BARE & WET %	[illegible] %	[illegible] in POUCES	[illegible] %	[illegible] %	[illegible] in POUCES	[illegible] %	[illegible] in POUCES	[illegible] %	[illegible] %	SAND SABLE	CHEM CHIM	TIME HEURE (UTC)	REMARKS - OBSERVATIONS [illegible] MENTIONNER TOUT ÉTAT DE LA SURFACE. PRÉCISER SI LE DÉBLAIEMENT EST EN COURS ET LE TEMPS D'ACHÈVEMENT ESTIMÉ
	CLEARED DÉGAGÉE																
	REMAINING RESTANTE																
	CLEARED DÉGAGÉE																
	REMAINING RESTANTE																
	CLEARED DÉGAGÉE																
	REMAINING RESTANTE																

AVERAGE J.B.I./TAPLEY READING
INDICE J.B.I./TAPLEY

RUNWAY PISTE	AMBIENT TEMP °C AMBIANTE	TOTAL RUNWAY AVERAGE MOYENNE POUR TOUTE LA PISTE	TIME HEURE (UTC)

NOTE: IF THE CLEARED PORTION OF THE RUNWAY IS OFF CENTER THE REMAINING WIDTH ON BOTH SIDES SHOULD BE REPORTED

À NOTER: SI LA PARTIE DÉGAGÉE DE LA PISTE N'EST PAS CENTRÉE, LA LARGEUR RESTANTE DES DEUX CÔTÉS DOIT ÊTRE RAPPORTÉE

TAXIWAYS AND APRONS VOIES DE CIRCULATION ET AIRES DE TRAFIC																

TAXIWAY/APRON INFORMATION FOR **LOCAL DISTRIBUTION ONLY**

LES DONNÉES RELATIVES AUX VOIES DE CIRCULATION ET AUX AIRES DE TRAFIC RÉSERVÉES À **LA DIFFUSION LOCALE SEULEMENT**

[illegible] REPORT TO - COMPTE RENDU [illegible] À	HOUR (UTC) HEURE (UTC)	DAY JOUR	MONTH MOIS	YEAR ANNÉE	SIGNATURE

[illegible] (11-80)

X

ANALYSIS OF RUNWAY CONDITION FOR OTTAWA INTERNATIONAL AIRPORT
RUNWAY 14/32

ANALYSIS OF FREQUENCY OF EACH RUNWAY CONDITION

The frequency of runway conditions are calculated only using data for the time period from 6 am to 11 pm each day.

Average Percent of Time With Each Runway Condition

Condition	Nov	Dec	Jan	Feb	Mar
Rwy closed	1.1	0.7	1.7	1.8	0.4
Bare - dry	63.2	59.3	62.4	73.1	75.4
Bare - wet	25.6	11.4	9.0	6.5	14.7
Snow - cover	2.8	11.0	9.4	7.7	2.6
Snow - drift	0.0	0.8	0.5	0.9	0.2
Snow - patch	1.0	2.9	4.9	3.6	0.8
Ice - cover	3.8	12.0	9.3	5.7	5.1
Snow ovr ice	0.0	0.0	0.0	0.0	0.0
Slush cover	2.5	1.4	0.9	0.6	0.7
Frost	0.1	0.5	1.9	0.1	0.1
Total hours*	1960	2125	2123	1935	2110

* Number of hours on which percentages are based.

Percent of Time When Runway Condition BARE_DRY is in Range:

Condition	Nov	Dec	Jan	Feb	Mar
0 %	28.4	22.7	19.4	11.4	15.6
1 - 20 %	3.3	4.3	4.7	2.3	1.3
21 - 40 %	2.4	6.3	4.2	3.6	2.0
41 - 60 %	3.6	10.4	7.9	7.2	3.8
61 - 80 %	3.8	14.3	17.8	18.0	9.9
81 - 100 %	58.4	42.1	46.0	57.4	67.3
Total hours*	1960	2125	2123	1935	2110

```
Percent of Time When Runway Condition  BARE_WET  is in Range:
--------------------------------------------------------------
Condition         Nov        Dec        Jan        Feb        Mar
--------------------------------------------------------------
   0     %        64.4       77.6       84.5       82.5       63.3
  1 - 20 %         6.8        6.3        2.6        8.1       20.4
 21 - 40 %         2.9        5.2        3.8        2.7        3.2
 41 - 60 %         2.7        2.8        1.8        2.7        1.5
 61 - 80 %         2.7        3.1        3.1        2.5        1.3
 81 - 100 %       20.5        5.0        4.1        1.5       10.3
----------------------------------------------------------------
Total hours*      1960       2125       2123       1935       2110
----------------------------------------------------------------
```

```
Percent of Time When Runway Condition  SNOW_COV  is in Range:
--------------------------------------------------------------
Condition         Nov        Dec        Jan        Feb        Mar
--------------------------------------------------------------
   0     %        95.8       74.0       78.5       80.4       93.5
  1 - 20 %         0.5       12.6        9.6        9.2        2.5
 21 - 40 %         0.3        3.5        3.7        2.8        1.7
 41 - 60 %         1.7        2.8        1.6        3.7        1.1
 61 - 80 %         0.0        1.0        1.7        1.0        0.4
 81 - 100 %        1.7        6.1        5.0        2.9        0.9
----------------------------------------------------------------
Total hours*      1960       2125       2123       1935       2110
----------------------------------------------------------------
```

```
Percent of Time When Runway Condition  SNOW_DRF  is in Range:
--------------------------------------------------------------
Condition         Nov        Dec        Jan        Feb        Mar
--------------------------------------------------------------
   0     %       100.0       97.1       98.2       96.3       99.1
  1 - 20 %         0.0        2.0        1.3        1.3        0.5
 21 - 40 %         0.0        0.5        0.1        2.2        0.4
 41 - 60 %         0.0        0.0        0.2        0.1        0.0
 61 - 80 %         0.0        0.0        0.2        0.0        0.0
 81 - 100 %        0.0        0.3        0.0        0.0        0.0
----------------------------------------------------------------
Total hours*      1960       2125       2123       1935       2110
----------------------------------------------------------------
```

Percent of Time When Runway Condition *SNOW_PAT* is in Range:

Condition	Nov	Dec	Jan	Feb	Mar
0 %	95.0	81.8	69.9	74.2	96.7
1 - 20 %	3.5	15.7	26.5	23.1	2.2
21 - 40 %	1.2	1.4	1.9	1.6	0.7
41 - 60 %	0.1	0.2	0.0	0.6	0.3
61 - 80 %	0.1	0.8	0.7	0.6	0.1
81 - 100 %	0.1	0.2	0.9	0.0	0.0
Total hours*	1960	2125	2123	1935	2110

Percent of Time When Runway Condition ICE_COV is in Range:

Condition	Nov	Dec	Jan	Feb	Mar
0 %	83.1	60.8	63.8	66.2	73.0
1 - 20 %	12.1	24.0	20.4	27.7	20.7
21 - 40 %	2.1	4.4	10.0	3.6	3.2
41 - 60 %	0.9	5.4	2.9	0.8	1.2
61 - 80 %	0.4	1.8	1.2	0.7	1.0
81 - 100 %	1.3	3.6	1.7	1.0	0.8
Total hours*	1960	2125	2123	1935	2110

Percent of Time When Runway Condition *SLUSH* is in Range:

Condition	Nov	Dec	Jan	Feb	Mar
0 %	94.0	94.0	96.1	97.4	97.5
1 - 20 %	2.4	4.4	2.6	1.6	1.5
21 - 40 %	0.7	0.8	0.9	0.8	0.5
41 - 60 %	1.8	0.6	0.1	0.0	0.4
61 - 80 %	0.0	0.0	0.3	0.1	0.0
81 - 100 %	1.0	0.3	0.0	0.1	0.1
Total hours*	1960	2125	2123	1935	2110

```
Percent of Time When Runway Condition  FROST  is in Range:
----------------------------------------------------------------
Condition          Nov        Dec        Jan        Feb        Mar
----------------------------------------------------------------
   0    %         99.8       98.9       95.8       99.8       99.9
  1 - 20 %         0.0        0.4        0.4        0.0        0.0
 21 - 40 %         0.2        0.3        2.2        0.2        0.0
 41 - 60 %         0.0        0.1        0.4        0.0        0.0
 61 - 80 %         0.0        0.0        0.8        0.0        0.0
 81 - 100 %        0.0        0.4        0.4        0.1        0.1
------------------------------------------------------------------
Total hours*     1960       2125       2123       1935       2110
------------------------------------------------------------------

Percent of Time When Runway Condition  SNOW_COV+SNOW_DRF+SNOW_PAT
 is in Range:
----------------------------------------------------------------
Condition          Nov        Dec        Jan        Feb        Mar
----------------------------------------------------------------
   0    %         91.8       57.0       52.4       57.2       89.7
  1 - 20 %         3.2       25.5       29.5       26.6        4.6
 21 - 40 %         1.1        5.8        7.4        6.5        2.8
 41 - 60 %         1.1        3.1        2.3        4.7        1.2
 61 - 80 %         1.0        1.9        2.2        1.8        0.7
 81 - 100 %        1.7        6.6        6.3        3.0        0.9
------------------------------------------------------------------
Total hours*     1960       2125       2123       1935       2110
------------------------------------------------------------------

Average Percent of Time With Each Runway Condition
Given % Ice cover is in range:   0 ,   0
[Given that ice cover is in given range, the probability that any
 given patch of runway is in the following condition is:]
----------------------------------------------------------------
Condition          Nov        Dec        Jan        Feb        Mar
----------------------------------------------------------------
Rwy closed        1.30       1.22       2.61       2.78       0.61
Bare - dry       63.07      62.87      61.95      72.65      77.03
Bare - wet       28.90      13.35      10.84       6.83      17.98
Snow - cover      3.37      16.61      13.68      10.99       2.76
Snow - drift      0.00       0.89       0.68       1.24       0.05
Snow - patch      0.86       2.92       6.97       4.44       0.74
Ice - cover       0.00       0.00       0.00       0.00       0.00
Snow ovr ice      0.00       0.00       0.00       0.00       0.00
Slush cover       2.41       1.48       0.75       0.90       0.73
Frost             0.07       0.66       2.52       0.19       0.11
------------------------------------------------------------------
Ice  0 - 0 % 1629.5     1292.1     1355.0     1280.9     1540.4 hrs
Percent          83.12      60.82      63.84      66.19      73.00
Total hours*     1960       2125       2123       1935       2110
------------------------------------------------------------------
```

```
Average Percent of Time With Each Runway Condition
Given % Ice cover is in range:   1 ,  20
---------------------------------------------------------------
Condition        Nov       Dec       Jan       Feb       Mar
---------------------------------------------------------------
Rwy closed       0.00      0.00      0.00      0.00      0.00
Bare - dry      84.02     71.79     81.96     82.87     83.36
Bare - wet       5.87      8.72      5.10      5.00      6.01
Snow - cover     0.00      3.12      1.49      0.52      0.91
Snow - drift     0.00      0.90      0.12      0.00      0.50
Snow - patch     0.94      2.98      1.22      2.18      0.11
Ice - cover      7.80     10.93      9.10      9.31      8.81
Snow ovr ice     0.00      0.00      0.00      0.00      0.00
Slush cover      1.35      1.19      0.68      0.12      0.27
Frost            0.00      0.36      0.34      0.00      0.02
-----------------------------------------------------------------
Ice  1- 20 %   238.0     510.3     433.2     536.0     437.8 hrs
Percent         12.14     24.02     20.41     27.70     20.74
Total hours*    1960      2125      2123      1935      2110
-----------------------------------------------------------------
```

```
Average Percent of Time With Each Runway Condition
Given % Ice cover is in range:  21 ,  40
---------------------------------------------------------------
Condition        Nov       Dec       Jan       Feb       Mar
---------------------------------------------------------------
Rwy closed       0.00      0.00      0.00      0.00      0.00
Bare - dry      19.71     40.85     53.03     48.04     51.49
Bare - wet      34.65     15.63      7.70     12.24      4.47
Snow - cover     0.00      2.20      1.62      3.87      5.20
Snow - drift     0.00      0.00      0.16      2.79      1.13
Snow - patch     5.60      4.46      1.13      1.41      0.00
Ice - cover     37.12     34.87     33.87     31.64     33.41
Snow ovr ice     0.00      0.00      0.00      0.00      0.00
Slush cover      2.93      2.44      2.20      0.00      4.30
Frost            0.00      0.00      0.29      0.00      0.00
-----------------------------------------------------------------
Ice 21- 40 %    40.6      94.2     212.8      69.3      67.7 hrs
Percent          2.07      4.43     10.02      3.58      3.21
Total hours*    1960      2125      2123      1935      2110
-----------------------------------------------------------------
```

Average Percent of Time With Each Runway Condition
Given % Ice cover is in range: 41 , 60

Condition	Nov	Dec	Jan	Feb	Mar
Rwy closed	0.00	0.00	0.00	0.00	0.00
Bare - dry	11.75	30.37	21.75	26.94	19.22
Bare - wet	2.97	7.48	10.19	9.49	10.69
Snow - cover	0.00	0.37	2.59	5.18	0.00
Snow - drift	0.00	0.00	1.00	0.00	2.56
Snow - patch	0.93	2.83	1.54	0.00	15.75
Ice - cover	56.90	56.32	54.11	56.77	51.78
Snow ovr ice	0.00	0.00	0.00	0.00	0.00
Slush cover	27.45	1.93	1.23	1.62	0.00
Frost	0.00	0.72	7.59	0.00	0.00
Ice 41- 60 %	18.0	113.9	60.6	15.9	26.0 hrs
Percent	0.92	5.36	2.85	0.82	1.23
Total hours*	1960	2125	2123	1935	2110

Average Percent of Time With Each Runway Condition
Given % Ice cover is in range: 61 , 80

Condition	Nov	Dec	Jan	Feb	Mar
Rwy closed	0.00	0.00	0.00	0.00	0.00
Bare - dry	6.69	16.92	12.72	12.71	3.29
Bare - wet	23.76	2.22	0.33	4.57	0.69
Snow - cover	0.00	0.31	6.07	9.15	20.06
Snow - drift	0.00	0.00	0.00	0.00	0.00
Snow - patch	0.00	1.69	3.35	0.00	0.00
Ice - cover	69.56	78.69	77.54	73.57	74.83
Snow ovr ice	0.00	0.00	0.00	0.00	0.00
Slush cover	0.00	0.16	0.00	0.00	1.12
Frost	0.00	0.00	0.00	0.00	0.00
Ice 61- 80 %	8.7	37.2	25.8	13.5	20.9 hrs
Percent	0.44	1.75	1.21	0.70	0.99
Total hours*	1960	2125	2123	1935	2110

```
Average Percent of Time With Each Runway Condition
Given % Ice cover is in range:  81 , 100
--------------------------------------------------------------
Condition          Nov        Dec        Jan        Feb        Mar
--------------------------------------------------------------
Rwy closed        0.00       0.00       0.00       0.00       0.00
Bare - dry        0.00       2.54       3.15       0.24       0.00
Bare - wet        1.93       0.55       0.00       2.93       1.58
Snow - cover      0.00       0.00       0.99       0.00       0.00
Snow - drift      0.00       0.45       0.00       0.00       0.00
Snow - patch      0.00       0.00       0.00       0.00       0.00
Ice - cover      98.07      96.26      95.56      96.83      98.42
Snow ovr ice      0.00       0.00       0.00       0.00       0.00
Slush cover       0.00       0.20       0.00       0.00       0.00
Frost             0.00       0.00       0.31       0.00       0.00
----------------------------------------------------------------
Ice 81-100 %      25.5       76.8       35.3       19.4       17.4 hrs
Percent           1.30       3.61       1.66       1.01       0.83
Total hours*      1960       2125       2123       1935       2110
----------------------------------------------------------------


ANALYSIS OF TAPLEY READINGS UNDER GIVEN RUNWAY CONDITIONS
-----------------------------------------------------------

Distribution of Tapley Readings for Condition BARE_DRY
----------------------------------------------------------------
Tapley        BARE_DRY < 51        BARE_DRY >= 51          Total
Reading          No.       %          No.        %           No.      %
----------------------------------------------------------------
  0.00           10       2.9          45       4.2           55     3.9
  0.20            0       0.0           1       0.1            1     0.1
  0.25            5       1.4          11       1.0           16     1.1
  0.29            1       0.3           0       0.0            1     0.1
  0.30           20       5.8          10       0.9           30     2.1
  0.35           25       7.2          23       2.2           48     3.4
  0.40           26       7.5          24       2.3           50     3.5
  0.45           21       6.1           4       0.4           25     1.8
> 0.50          239      68.9         947      88.9         1186    84.0
----------------------------------------------------------------
Total           347      24.6        1065      75.4         1412
----------------------------------------------------------------
```

Distribution of Tapley Readings for Condition BARE_WET

Tapley	BARE_WET < 51		BARE_WET >= 51		Total	
Reading	No.	%	No.	%	No.	%
0.00	13	3.7	36	12.1	49	7.6
0.25	3	0.9	0	0.0	3	0.5
0.30	2	0.6	0	0.0	2	0.3
0.35	8	2.3	0	0.0	8	1.2
0.40	14	4.0	0	0.0	14	2.2
0.45	9	2.6	1	0.3	10	1.5
> 0.50	300	86.0	261	87.6	561	86.7
Total	349	53.9	298	46.1	647	

Distribution of Tapley Readings for Condition SNOW_COV

Tapley	SNOW_COV < 51		SNOW_COV >= 51		Total	
Reading	No.	%	No.	%	No.	%
0.00	3	0.9	1	0.5	4	0.7
0.20	1	0.3	5	2.3	6	1.1
0.25	3	0.9	10	4.5	13	2.4
0.30	10	3.1	23	10.4	33	6.1
0.35	15	4.7	25	11.3	40	7.4
0.37	0	0.0	1	0.5	1	0.2
0.40	9	2.8	25	11.3	34	6.3
0.45	5	1.6	16	7.2	21	3.9
> 0.50	273	85.6	115	52.0	388	71.9
Total	319	59.1	221	40.9	540	

Distribution of Tapley Readings for Condition SNOW_DRF

Tapley	SNOW_DRF < 51		SNOW_DRF >= 51		Total	
Reading	No.	%	No.	%	No.	%
0.35	2	4.5	0	0.0	2	3.8
0.40	3	6.8	0	0.0	3	5.7
0.45	3	6.8	1	11.1	4	7.5
> 0.50	36	81.8	8	88.9	44	83.0
Total	44	83.0	9	17.0	53	

Distribution of Tapley Readings for Condition SNOW_PAT

Tapley	SNOW_PAT < 51		SNOW_PAT >= 51		Total	
Reading	No.	%	No.	%	No.	%
0.20	1	0.3	0	0.0	1	0.3
0.25	2	0.6	2	8.3	4	1.2
0.30	6	1.9	4	16.7	10	3.0
0.35	9	2.9	7	29.2	16	4.7
0.40	12	3.8	3	12.5	15	4.5
0.45	6	1.9	1	4.2	7	2.1
> 0.50	277	88.5	7	29.2	284	84.3
Total	313	92.9	24	7.1	337	

Distribution of Tapley Readings for Condition ICE_COV

Tapley	ICE_COV < 51		ICE_COV >= 51		Total	
Reading	No.	%	No.	%	No.	%
0.15	0	0.0	2	1.2	2	0.3
0.20	1	0.2	5	3.0	6	0.9
0.25	3	0.6	22	13.3	25	3.7
0.28	0	0.0	1	0.6	1	0.1
0.29	0	0.0	1	0.6	1	0.1
0.30	12	2.3	25	15.2	37	5.4
0.35	10	1.9	38	23.0	48	7.0
0.40	17	3.3	27	16.4	44	6.4
0.45	9	1.7	10	6.1	19	2.8
> 0.50	467	90.0	34	20.6	501	73.2
Total	519	75.9	165	24.1	684	

Distribution of Tapley Readings for Condition SLUSH

Tapley	SLUSH < 51		SLUSH >= 51		Total	
Reading	No.	%	No.	%	No.	%
0.00	2	1.4	3	9.4	5	2.9
0.20	0	0.0	1	3.1	1	0.6
0.25	3	2.1	1	3.1	4	2.3
0.30	2	1.4	0	0.0	2	1.2
0.35	3	2.1	1	3.1	4	2.3
0.40	1	0.7	1	3.1	2	1.2
0.45	2	1.4	0	0.0	2	1.2
> 0.50	128	90.8	25	78.1	153	88.4
Total	141	81.5	32	18.5	173	

Distribution of Tapley Readings for Condition FROST

Tapley Reading	FROST < 51 No.	%	FROST >= 51 No.	%	Total No.	%
0.30	0	0.0	1	10.0	1	3.3
0.32	0	0.0	1	10.0	1	3.3
0.35	1	5.0	2	20.0	3	10.0
0.40	3	15.0	3	30.0	6	20.0
0.45	1	5.0	0	0.0	1	3.3
> 0.50	15	75.0	3	30.0	18	60.0
Total	20	66.7	10	33.3	30	

ANALYSIS OF COMMENTS GIVEN FOR EACH RUNWAY CONDITION

Distribution of Runway Condition Descriptors for BARE_WET

Condition Descriptor	BARE_WET < 51 No.	%	BARE_WET >= 51 No.	%	Total No.	%
	339	97.1	297	99.7	636	98.3
.75"	1	0.3	0	0.0	1	0.2
p	9	2.6	0	0.0	9	1.4
swep	0	0.0	1	0.3	1	0.2
Total	349	53.9	298	46.1	647	

```
Distribution of Runway Condition Descriptors for  SNOW_COV
==================================================================
Condition    SNOW_COV < 51       SNOW_COV >= 51          Total
Descriptor     No.        %           No.        %          No.      %
==================================================================
               196      61.4         115      52.0         311     7.6
   .13           1       0.3           5       2.3           6     1.1
   .25          21       6.6          36      16.3          57    10.6
   .25p          1       0.3           0       0.0           1     0.2
   .3            3       0.9          15       6.8          18     3.3
   .5           23       7.2          15       6.8          38     7.0
   .5-1          0       0.0           1       0.5           1     0.2
   .5p           1       0.3           0       0.0           1     0.2
   .75           2       0.6          14       6.3          16     3.0
   1            11       3.4           5       2.3          16     3.0
   1-2           2       0.6           0       0.0           2     0.4
   1.5           3       0.9           2       0.9           5     0.9
   2             6       1.9           1       0.5           7     1.3
   2-3           0       0.0           1       0.5           1     0.2
   3-4           1       0.3           0       0.0           1     0.2
   d             3       0.9           0       0.0           3     0.6
   drif          1       0.3           0       0.0           1     0.2
   lit           0       0.0           3       1.4           3     0.6
   loos          1       0.3           0       0.0           1     0.2
   p            41      12.9           2       0.9          43     8.0
   wet           2       0.6           6       2.7           8     1.5
==================================================================
  Total        319      59.1         221      40.9         540
==================================================================

Distribution of Runway Condition Descriptors for  SNOW_DRF
==================================================================
Condition    SNOW_DRF < 51       SNOW_DRF >= 51          Total
Descriptor     No.        %           No.        %          No.      %
==================================================================
                 1       2.3           2      22.2           3     5.7
   .13           0       0.0           1      11.1           1     1.9
   .25           6      13.6           0       0.0           6    11.3
   .3            2       4.5           2      22.2           4     7.5
   .5           15      34.1           1      11.1          16    30.2
   1             4       9.1           0       0.0           4     7.5
   1-2           1       2.3           0       0.0           1     1.9
   1.5           3       6.8           1      11.1           4     7.5
   2             4       9.1           0       0.0           4     7.5
   2-4           2       4.5           0       0.0           2     3.8
   4             1       2.3           0       0.0           1     1.9
   d=.5          2       4.5           0       0.0           2     3.8
   ds            3       6.8           2      22.2           5     9.4
==================================================================
  Total         44      83.0           9      17.0          53
==================================================================
Distribution of Runway Condition Descriptors for  SNOW_PAT
=================================================================
Condition   SNOW_PAT < 51     SNOW_PAT >= 51          Total
Descriptor    No.       %         No.        %         No.      %
=================================================================
              156      49.8        15      62.5       171    50.7
   .25          1       0.3         1       4.2         2     0.6
   .3           0       0.0         4      16.7         4     1.2
   .5-1         1       0.3         1       4.2         2     0.6
   >5           0       0.0         1       4.2         1     0.3
   c            4       1.3         2       8.3         6     1.8
   lite         1       0.3         0       0.0         1     0.3
   p          149      47.6         0       0.0       149    44.2
   wet          1       0.3         0       0.0         1     0.3
=================================================================
  Total       313      92.9        24       7.1       337
=================================================================


Distribution of Runway Condition Descriptors for  ICE_COV
=================================================================
Condition   ICE_COV < 51     ICE_COV >= 51          Total
Descriptor    No.       %         No.        %         No.      %
=================================================================
               59      11.4        48      29.1       107    15.6
   c           33       6.4        83      50.3       116    17.0
   lit          0       0.0         1       0.6         1     0.1
   p          396      76.3        10       6.1       406    59.4
   s            0       0.0         6       3.6         6     0.9
   thin         0       0.0         1       0.6         1     0.1
   wet         15       2.9        16       9.7        31     4.5
   wetc         4       0.8         0       0.0         4     0.6
   wetp        12       2.3         0       0.0        12     1.8
=================================================================
  Total       519      75.9       165      24.1       684
=================================================================


Distribution of Runway Condition Descriptors for  SLUSH
=================================================================
Condition   SLUSH < 51     SLUSH >= 51          Total
Descriptor    No.       %         No.        %         No.      %
=================================================================
                2       1.4         3       9.4         5     2.9
   .25        139      98.6        29      90.6       168    97.1
=================================================================
  Total       141      81.5        32      18.5       173
=================================================================
```

X

```
Distribution of Runway Condition Descriptors for  FROST
===============================================================
Condition     FROST < 51      FROST >= 51          Total
Descriptor     No.       %         No.       %          No.       %
===============================================================
               18      90.0        10     100.0         28     93.3
   ip           1       5.0         0       0.0          1      3.3
   p            1       5.0         0       0.0          1      3.3
===============================================================
  Total        20      66.7        10      33.3         30
===============================================================
```

ANALYSIS OF RUNWAY CONDITION FOR CALGARY INTERNATIONAL AIRPORT
RUNWAY 16/34

ANALYSIS OF FREQUENCY OF EACH RUNWAY CONDITION

The frequency of runway conditions are calculated only using data for the time period from 6 am to 11 pm each day.

Average Percent of Time With Each Runway Condition
[probability that any given patch of runway has the following runway condition]

Condition	Nov	Dec	Jan	Feb	Mar
Bare - dry	91.0	81.8	88.0	84.9	89.3
Bare - wet	4.0	4.6	1.8	3.2	5.5
Snow - loose	1.9	9.1	5.4	7.8	2.4
Snow - drift	0.2	0.2	1.0	0.1	0.0
Snow - compt	0.8	0.4	0.5	0.9	0.7
Ice - patch	1.9	2.9	1.6	1.2	1.7
Slush cover	0.2	0.5	0.4	0.7	0.2
Frost	0.0	0.5	1.3	1.2	0.1
Total hours*	1551	1575	1022	969	1326

* Number of hours on which percentages are based.

Percent of Time When Runway Condition BARE_DRY is in Range:

Condition	Nov	Dec	Jan	Feb	Mar
0 %	4.4	8.0	4.5	7.3	4.7
1 - 20 %	1.0	1.9	1.0	1.9	1.8
21 - 40 %	3.2	1.4	1.2	1.2	2.2
41 - 60 %	1.1	8.9	3.3	7.0	2.5
61 - 80 %	2.6	10.2	8.0	3.1	5.4
81 - 100 %	87.6	69.6	81.9	79.5	83.3
Total hours*	1561	1575	1022	969	1303

Percent of Time When Runway Condition BARE_WET is in Range:

Condition	Nov	Dec	Jan	Feb	Mar
0 %	90.6	91.6	92.0	94.4	88.1
1 - 20 %	2.9	2.2	5.8	0.6	5.5
21 - 40 %	1.1	1.8	0.7	2.1	1.2
41 - 60 %	3.9	0.5	0.6	0.5	0.4
61 - 80 %	0.0	1.2	0.0	0.0	1.5
81 - 100 %	1.5	2.7	1.0	2.4	3.2
Total hours*	1561	1575	1022	969	1303

Percent of Time When Runway Condition LOOSE_SNOW is in Range:

Condition	Nov	Dec	Jan	Feb	Mar
0 %	94.6	77.9	76.5	77.3	94.0
1 - 20 %	2.8	8.0	16.2	10.3	2.4
21 - 40 %	0.5	3.7	3.2	5.3	1.2
41 - 60 %	1.2	6.2	2.1	2.6	0.7
61 - 80 %	0.3	2.4	0.5	2.6	0.7
81 - 100 %	0.5	1.9	1.5	1.9	1.0
Total hours*	1561	1575	1022	969	1303

Percent of Time When Runway Condition COMPACT_SNOW is in Range:

Condition	Nov	Dec	Jan	Feb	Mar
0 %	96.6	94.7	90.8	91.0	95.3
1 - 20 %	2.2	5.1	9.1	8.6	3.7
21 - 40 %	0.9	0.2	0.1	0.0	1.0
41 - 60 %	0.1	0.0	0.0	0.5	0.0
61 - 80 %	0.0	0.0	0.0	0.0	0.0
81 - 100 %	0.3	0.0	0.0	0.0	0.0
Total hours*	1561	1575	1022	969	1303

```
Percent of Time When Runway Condition  SNOW_DRIFT  is in Range:
=================================================================
Condition          Nov          Dec          Jan          Feb          Mar
=================================================================
    0     %       99.7         99.0         96.6         99.1         99.8
  1 - 20 %         0.0          0.6          1.0          0.9          0.2
 21 - 40 %         0.0          0.3          1.7          0.0          0.0
 41 - 60 %         0.3          0.1          0.7          0.0          0.0
 61 - 80 %         0.0          0.0          0.0          0.0          0.0
 81 - 100 %        0.0          0.0          0.0          0.0          0.0
=================================================================
Total hours*      1561         1575         1022          969         1303
=================================================================

Percent of Time When Runway Condition  SLUSH  is in Range:
=================================================================
Condition          Nov          Dec          Jan          Feb          Mar
=================================================================
    0     %       99.5         97.9         99.3         98.8         99.3
  1 - 20 %         0.1          1.3          0.0          0.0          0.3
 21 - 40 %         0.2          0.2          0.0          0.5          0.4
 41 - 60 %         0.0          0.3          0.4          0.5          0.0
 61 - 80 %         0.2          0.0          0.0          0.0          0.0
 81 - 100 %        0.0          0.2          0.2          0.3          0.0
=================================================================
Total hours*      1561         1575         1022          969         1303
=================================================================

Percent of Time When Runway Condition  FROST  is in Range:
=================================================================
Condition          Nov          Dec          Jan          Feb          Mar
=================================================================
    0     %      100.0         98.6         97.1         97.3         99.4
  1 - 20 %         0.0          0.8          1.5          1.8          0.6
 21 - 40 %         0.0          0.4          0.1          0.1          0.0
 41 - 60 %         0.0          0.0          0.6          0.0          0.0
 61 - 80 %         0.0          0.0          0.3          0.2          0.0
 81 - 100 %        0.0          0.3          0.5          0.7          0.0
=================================================================
Total hours*      1561         1575         1022          969         1303
=================================================================
```

Percent of Time When Runway Condition ICE_PATCHES is in Range:

Condition	Nov	Dec	Jan	Feb	Mar
0 %	91.5	88.7	89.5	97.1	94.4
1 - 20 %	5.9	7.9	9.1	0.8	3.1
21 - 40 %	1.4	1.4	0.1	1.2	1.7
41 - 60 %	0.4	1.4	0.9	0.2	0.3
61 - 80 %	0.8	0.2	0.4	0.1	0.2
81 - 100 %	0.0	0.4	0.0	0.6	0.3
Total hours*	1561	1575	1022	969	1303

ANALYSIS OF TAPLEY READINGS UNDER GIVEN RUNWAY CONDITIONS

Distribution of Tapley Readings for Condition BARE_DRY

Tapley	BARE_DRY < 51 %		BARE_DRY >= 51 %		Total	
Readirg	No.	%	No.	%	No.	%
0.25 - 0.29	1	0.9	0	0.0	1	0.1
0.30 - 0.34	6	5.5	0	0.0	6	0.8
0.35 - 0.39	6	5.5	2	0.3	8	1.0
0.40 - 0.44	10	9.2	2	0.3	12	1.6
0.45 - 0.49	17	15.6	5	0.8	22	2.9
0.50 - 0.54	15	13.8	7	1.1	22	2.9
0.55 - 0.59	8	7.3	6	0.9	14	1.8
0.60 - 0.64	13	11.9	15	2.3	28	3.7
0.65 - 0.69	12	11.0	23	3.5	35	4.6
0.70 - 0.74	7	6.4	16	2.4	23	3.0
0.75 - 0.79	2	1.8	13	2.0	15	2.0
0.80 - 0.84	4	3.7	41	6.2	45	5.9
0.85 - 0.89	2	1.8	34	5.2	36	4.7
0.90 - 0.94	0	0.0	31	4.7	31	4.0
0.95 - 0.99	0	0.0	9	1.4	9	1.2
Not given	6	5.5	454	69.0	460	60.0
Total	109	14.2	658	85.8	767	

Distribution of Tapley Readings for Condition BARE_WET

Tapley	BARE_WET < 51 %		BARE_WET >= 51 %		Total	
Reading	No.	%	No.	%	No.	%
0.25 - 0.29	1	1.7	0	0.0	1	0.9
0.30 - 0.34	5	8.6	0	0.0	5	4.5
0.35 - 0.39	3	5.2	0	0.0	3	2.7
0.40 - 0.44	5	8.6	1	1.9	6	5.4
0.45 - 0.49	3	5.2	0	0.0	3	2.7
0.50 - 0.54	3	5.2	3	5.6	6	5.4
0.55 - 0.59	3	5.2	2	3.7	5	4.5
0.60 - 0.64	4	6.9	5	9.3	9	8.0
0.65 - 0.69	1	1.7	5	9.3	6	5.4
0.70 - 0.74	3	5.2	3	5.6	6	5.4
0.75 - 0.79	3	5.2	4	7.4	7	6.3
0.80 - 0.84	4	6.9	1	1.9	5	4.5
0.85 - 0.89	1	1.7	1	1.9	2	1.8
0.90 - 0.94	3	5.2	0	0.0	3	2.7
0.95 - 0.99	1	1.7	0	0.0	1	0.9
Not given	15	25.9	29	53.7	44	39.3
Total	58	51.8	54	48.2	112	

Distribution of Tapley Readings for Condition LOOSE_SNOW

Tapley	LOOSE_SNOW < 51%		LOOSE_SNOW >= 51%		Total	
Reading	No.	%	No.	%	No.	%
0.25 - 0.29	0	0.0	4	5.3	4	1.6
0.30 - 0.34	4	2.4	14	18.7	18	7.4
0.35 - 0.39	6	3.6	10	13.3	16	6.6
0.40 - 0.44	4	2.4	11	14.7	15	6.2
0.45 - 0.49	9	5.4	8	10.7	17	7.0
0.50 - 0.54	15	8.9	3	4.0	18	7.4
0.55 - 0.59	12	7.1	1	1.3	13	5.3
0.60 - 0.64	15	8.9	5	6.7	20	8.2
0.65 - 0.69	28	16.7	6	8.0	34	14.0
0.70 - 0.74	10	6.0	6	8.0	16	6.6
0.75 - 0.79	9	5.4	0	0.0	9	3.7
0.80 - 0.84	12	7.1	4	5.3	16	6.6
0.85 - 0.89	15	8.9	0	0.0	15	6.2
0.90 - 0.94	7	4.2	0	0.0	7	2.9
0.95 - 0.99	1	0.6	0	0.0	1	0.4
Not given	21	12.5	3	4.0	24	9.9
Total	168	69.1	75	30.9	243	

```
Distribution of Tapley Readings for Condition COMPACT_SNOW
===================================================================
Tapley         COMPACT_SNOW <51%   COMPACT_SNOW >=51%       Total
Reading             No.      %         No.        %       No.       %
===================================================================
0.30 -  0.34         3      4.8         0        0.0        3      4.7
0.35 -  0.39         2      3.2         0        0.0        2      3.1
0.40 -  0.44         2      3.2         0        0.0        2      3.1
0.45 -  0.49         4      6.5         1       50.0        5      7.8
0.50 -  0.54         2      3.2         1       50.0        3      4.7
0.55 -  0.59         1      1.6         0        0.0        1      1.6
0.65 -  0.69         2      3.2         0        0.0        2      3.1
0.70 -  0.74         4      6.5         0        0.0        4      6.3
0.75 -  0.79         3      4.8         0        0.0        3      4.7
0.80 -  0.84        10     16.1         0        0.0       10     15.6
0.85 -  0.89         9     14.5         0        0.0        9     14.1
0.90 -  0.94         9     14.5         0        0.0        9     14.1
Not given           11     17.7         0        0.0       11     17.2
==================================================================
Total               62     96.9         2        3.1       64
==================================================================


Distribution of Tapley Readings for Condition SNOW_DRIFT
===================================================================
Tapley           SNOW_DRF < 51 %   SNOW_DRF >= 51 %       Total
Reading             No.      %         No.        %       No.       %
===================================================================
0.25 -  0.29         1      5.9         0        0.0        1      5.6
0.30 -  0.34         0      0.0         1      100.0        1      5.6
0.35 -  0.39         2     11.8         0        0.0        2     11.1
0.50 -  0.54         1      5.9         0        0.0        1      5.6
0.60 -  0.64         3     17.6         0        0.0        3     16.7
0.65 -  0.69         2     11.8         0        0.0        2     11.1
0.70 -  0.74         2     11.8         0        0.0        2     11.1
0.80 -  0.84         3     17.6         0        0.0        3     16.7
0.85 -  0.89         1      5.9         0        0.0        1      5.6
Not given            2     11.8         0        0.0        2     11.1
==================================================================
Total               17     94.4         1        5.6       18
==================================================================
```

Distribution of Tapley Readings for Condition SLUSH

Tapley	SLUSH < 51 %		SLUSH >= 51 %		Total	
Reading	No.	%	No.	%	No.	%
0.25 - 0.29	3	11.5	0	0.0	3	9.7
0.30 - 0.34	1	3.8	1	20.0	2	6.5
0.35 - 0.39	3	11.5	0	0.0	3	9.7
0.40 - 0.44	3	11.5	0	0.0	3	9.7
0.45 - 0.49	0	0.0	2	40.0	2	6.5
0.55 - 0.59	4	15.4	0	0.0	4	12.9
0.60 - 0.64	1	3.8	0	0.0	1	3.2
0.65 - 0.69	3	11.5	0	0.0	3	9.7
Not given	8	30.8	2	40.0	10	32.3
Total	26	83.9	5	16.1	31	

Distribution of Tapley Readings for Condition FROST

Tapley	FROST < 51 %		FROST >= 51 %		Total	
Reading	No.	%	No.	%	No.	%
0.20 - 0.24	0	0.0	1	7.7	1	3.4
0.25 - 0.29	1	6.3	0	0.0	1	3.4
0.30 - 0.34	1	6.3	4	30.8	5	17.2
0.35 - 0.39	3	18.8	2	15.4	5	17.2
0.40 - 0.44	1	6.3	4	30.8	5	17.2
0.45 - 0.49	1	6.3	1	7.7	2	6.9
0.50 - 0.54	2	12.5	1	7.7	3	10.3
0.55 - 0.59	1	6.3	0	0.0	1	3.4
0.60 - 0.64	2	12.5	0	0.0	2	6.9
0.70 - 0.74	2	12.5	0	0.0	2	6.9
Not given	2	12.5	0	0.0	2	6.9
Total	16	55.2	13	44.8	29	

```
Distribution of Tapley Readings for Condition ICE_PATCHES
=========================================================================
Tapley              ICE_PAT < 51 %      ICE_PAT >= 51 %        Total
Reading             No.        %        No.         %         No.        %
=========================================================================
0.25 -   0.29         1        1.2        2        6.7           3      2.6
0.30 -   0.34         7        8.1        4       13.3          11      9.5
0.35 -   0.39         3        3.5        6       20.0           9      7.8
0.40 -   0.44         5        5.8        8       26.7          13     11.2
0.45 -   0.49         7        8.1        4       13.3          11      9.5
0.50 -   0.54         6        7.0        3       10.0           9      7.8
0.55 -   0.59         3        3.5        2        6.7           5      4.3
0.60 -   0.64         8        9.3        1        3.3           9      7.8
0.65 -   0.69         6        7.0        0        0.0           6      5.2
0.70 -   0.74         5        5.8        0        0.0           5      4.3
0.75 -   0.79         6        7.0        0        0.0           6      5.2
0.80 -   0.84        19       22.1        0        0.0          19     16.4
0.85 -   0.89         2        2.3        0        0.0           2      1.7
0.90 -   0.94         1        1.2        0        0.0           1      0.9
0.95 -   0.99         1        1.2        0        0.0           1      0.9
Not given             6        7.0        0        0.0           6      5.2
========================================================================
Total                86       74.1       30       25.9         116
========================================================================
```

```
ANALYSIS OF DEPTH OF CONTAMINANT FOR EACH RUNWAY CONDITION
==========================================================
```

```
Distribution of Runway Contamination Depth for  LOOSE_SNOW
=======================================================================
Depth        LOOSE_SNOW < 51%    LOOSE_SNOW >= 51%         Total
Inches           No.         %          No.        %          No.       %
=======================================================================
                 17       10.1            0      0.0           17     7.0
 .1              62       36.9           28     37.3           90    37.0
 .125            43       25.6           20     26.7           63    25.9
 .2               1        0.6            0      0.0            1     0.4
 .25             24       14.3           10     13.3           34    14.0
 .3               1        0.6            1      1.3            2     0.8
 .5              14        8.3           10     13.3           24     9.9
 .75              2        1.2            0      0.0            2     0.8
 1                2        1.2            3      4.0            5     2.1
 1.5              1        0.6            1      1.3            2     0.8
 2                1        0.6            1      1.3            2     0.8
 6                0        0.0            1      1.3            1     0.4
=======================================================================
Total           168       69.1           75     30.9          243
=======================================================================
Distribution of Runway Contamination Depth for  SNOW_DRIFT
======================================================================
Depth         SNOW_DRF < 51 %     SNOW_DRF >= 51 %          Total
Inches        No.          %      No.           %         No.        %
======================================================================
                1        5.9        0         0.0           1      5.6
 .1             1        5.9        0         0.0           1      5.6
 .125           3       17.6        1       100.0           4     22.2
 .25            3       17.6        0         0.0           3     16.7
 .5             3       17.6        0         0.0           3     16.7
 1              2       11.8        0         0.0           2     11.1
 1.5            1        5.9        0         0.0           1      5.6
 10             1        5.9        0         0.0           1      5.6
 3              2       11.8        0         0.0           2     11.1
======================================================================
Total          17       94.4        1         5.6          18
======================================================================


Distribution of Runway Contamination Depth for  SLUSH
======================================================================
Depth          SLUSH < 51 %          SLUSH >= 51 %          Total
Inches        No.          %      No.           %         No.        %
======================================================================
                3       11.5        1        20.0           4     12.9
 .1             4       15.4        1        20.0           5     16.1
 .125           4       15.4        0         0.0           4     12.9
 .25           11       42.3        2        40.0          13     41.9
 .5             2        7.7        0         0.0           2      6.5
 .6             1        3.8        0         0.0           1      3.2
 .66            0        0.0        1        20.0           1      3.2
 1              1        3.8        0         0.0           1      3.2
======================================================================
Total          26       83.9        5        16.1          31
======================================================================
```

RESULTS OF ANALYSES FOR EDMONTON INTERNATIONAL RUNWAY 01/19

ANALYSIS OF FREQUENCY OF EACH RUNWAY CONDITION - 1988-1990

Frequencies refer only to the period from 6 am to 11 pm. Runway conditions outside this time interval were not considered when determining the following percentages.

Average Percent of Time With Each Runway Condition
[probability that any given patch of runway has the following runway condition]

Condition	Nov	Dec	Jan	Feb	Mar
Bare - dry	90.7	65.1	73.3	73.1	87.6
Bare - wet	3.0	4.7	3.1	6.4	1.6
Snow - loose	2.7	9.7	9.5	8.6	3.9
Snow - drift	0.0	0.0	0.0	0.0	0.5
Snow - compt	2.0	2.9	1.5	2.3	0.9
Ice - patch	1.4	17.0	9.2	7.4	5.4
Slush cover	0.0	0.0	0.7	0.0	0.0
Frost	0.0	0.5	2.6	2.2	0.0
Total hours	1037	1037	1902	1421	765

* Hours of data on which percentages are based

Note: There were many extended time periods (more than 5 days) where the condition reports were not available and the runway conditions were not bare and dry. It was assumed that the conditions on the report were applicable for approximately one day and for the remainder of the period conditions were either bare and dry or bare and wet based on the probability of rain given no snow or freezing rain for that month. The extended time periods with no reports occured most frequently in November and March and the frequency of conditions for these months are therefore less reliable than for December, January and February.

```
ANALYSIS OF TAPLEY READINGS UNDER GIVEN RUNWAY CONDITIONS
=========================================================

Distribution of Tapley Readings for Condition BARE_DRY
======================================================================
Tapley      BARE_DRY < 51 %    BARE_DRY >= 51 %          Total
Reading         No.       %        No.        %          No.        %
======================================================================
  0.40           2      18.2        0       0.0            2      5.0
  0.45           1       9.1        0       0.0            1      2.5
  0.50           3      27.3        0       0.0            3      7.5
  0.60           1       9.1        4      13.8            5     12.5
  0.65           1       9.1        2       6.9            3      7.5
  0.70           0       0.0        2       6.9            2      5.0
  0.75           0       0.0        1       3.4            1      2.5
  0.80           0       0.0        2       6.9            2      5.0
Not given        3      27.3       18      62.1           21     52.5
======================================================================
Total           11      27.5       29      72.5           40
======================================================================


Distribution of Tapley Readings for Condition BARE_WET
======================================================================
Tapley      BARE_WET < 51 %    BARE_WET >= 51 %          Total
Reading         No.       %        No.        %          No.        %
======================================================================
  0.50           1      20.0        0       0.0            1      8.3
  0.60           1      20.0        0       0.0            1      8.3
  0.80           1      20.0        0       0.0            1      8.3
Not given        2      40.0        7     100.0            9     75.0
======================================================================
Total            5      41.7        7      58.3           12
======================================================================
Distribution of Tapley Readings for Condition LOOSE SNOW
===========================================================================
Tapley       LOOSE SNOW < 51 %     LOOSE SNOW >= 51 %          Total
Reading         No.        %          No.        %          No.        %
===========================================================================
  0.15           1       10.0           0       0.0           1       2.3
  0.20           0        0.0           1       3.0           1       2.3
  0.25           0        0.0           2       6.1           2       4.7
  0.30           3       30.0          19      57.6          22      51.2
  0.35           0        0.0           5      15.2           5      11.6
  0.40           0        0.0           1       3.0           1       2.3
  0.45           0        0.0           2       6.1           2       4.7
  0.50           0        0.0           1       3.0           1       2.3
  0.60           1       10.0           0       0.0           1       2.3
  0.65           1       10.0           0       0.0           1       2.3
  0.80           1       10.0           0       0.0           1       2.3
Not given        3       30.0           2       6.1           5      11.6
===========================================================================
Total           10       23.3          33      76.7          43
===========================================================================


Distribution of Tapley Readings for Condition COMPACT SNOW
===========================================================================
Tapley       COMPACTSNOW < 51 %    COMPACT SNOW >= 51 %        Total
Reading         No.        %          No.        %          No.        %
===========================================================================
  0.50           1        5.9           1     100.0           2      11.1
  0.60           1        5.9           0       0.0           1       5.6
  0.65           2       11.8           0       0.0           2      11.1
  0.70           2       11.8           0       0.0           2      11.1
  0.80           1        5.9           0       0.0           1       5.6
Not given       10       58.8           0       0.0          10      55.6
===========================================================================
Total           17       94.4           1       5.6          18
===========================================================================


Distribution of Tapley Readings for Condition SNOW_DRIFT
===========================================================================
Tapley       SNOW_DRIFT < 51 %     SNOW_DRIFT >= 51 %          Total
Reading         No.        %          No.        %          No.        %
===========================================================================
Not given        1      100.0           0 *********           1     100.0
===========================================================================
Total            1      100.0           0       0.0           1
===========================================================================
```

Distribution of Tapley Readings for Condition SLUSH

Tapley Reading	SLUSH < 51 % No.	%	SLUSH >= 51 % No.	%	Total No.	%
Not given	0	*********	1	100.0	1	100.0
Total	0	0.0	1	100.0	1	

Distribution of Tapley Readings for Condition FROST

Tapley Reading	FROST < 51 % No.	%	FROST >= 51 % No.	%	Total No.	%
0.30	0	0.0	1	16.7	1	12.5
0.35	0	0.0	1	16.7	1	12.5
0.40	0	0.0	1	16.7	1	12.5
0.45	0	0.0	1	16.7	1	12.5
0.50	0	0.0	2	33.3	2	25.0
Not given	2	100.0	0	0.0	2	25.0
Total	2	25.0	6	75.0	8	

Distribution of Tapley Readings for Condition ICE_PATCHES

Tapley Reading	ICE PATCHES < 51% No.	%	ICE PATCHES >= 51% No.	%	Total No.	%
0.10	0	0.0	1	4.3	1	2.4
0.15	1	5.3	0	0.0	1	2.4
0.20	0	0.0	1	4.3	1	2.4
0.25	0	0.0	1	4.3	1	2.4
0.30	2	10.5	6	26.1	8	19.0
0.35	1	5.3	3	13.0	4	9.5
0.40	0	0.0	3	13.0	3	7.1
0.45	0	0.0	3	13.0	3	7.1
0.50	2	10.5	1	4.3	3	7.1
0.55	0	0.0	2	8.7	2	4.8
0.60	4	21.1	2	8.7	6	14.3
0.65	2	10.5	0	0.0	2	4.8
0.75	1	5.3	0	0.0	1	2.4
Not given	6	31.6	0	0.0	6	14.3
Total	19	45.2	23	54.8	42	

ANALYSIS OF DEPTH OF CONTAMINANT GIVEN RUNWAY CONDITIONS

Distribution of Runway Contamination Depth for LOOSE SNOW

Depth	LOOSE SNOW < 51%		LOOSE SNOW >= 51%		Total	
Inches	No.	%	No.	%	No.	%
Not given	4	40.0	5	15.2	9	20.9
TRACE	0	0.0	2	6.1	2	4.7
.125	3	30.0	11	33.3	14	32.6
.25	1	10.0	11	33.3	12	27.9
.5	0	0.0	2	6.1	2	4.7
1	1	10.0	2	6.1	3	7.0
7	1	10.0	0	0.0	1	2.3
Total	10	23.3	33	76.7	43	

Distribution of Runway Contamination Depth for SNOW_DRIFT

Depth	SNOW_DRIFT < 51%		SNOW_DRIFT >= 51%		Total	
Inches	No.	%	No.	%	No.	%
6	1	100.0	0	*********	1	100.0
Total	1	100.0	0	0.0	1	

Distribution of Runway Contamination Depth for SLUSH

Depth	SLUSH < 51 %		SLUSH >= 51 %		Total	
Inches	No.	%	No.	%	No.	%
.25	0	*********	1	100.0	1	100.0
Total	0	0.0	1	100.0	1	

RESULTS OF ANALYSES FOR PRINCE GEORGE RUNWAY 15/33

ANALYSIS OF FREQUENCY OF EACH RUNWAY CONDITION

Frequencies refer only to the period from 6 am to 11 pm. Runway conditions outside this time interval were not considered when determining the following percentages.

Average Percent of Time With Each Runway Condition
[probability that any given patch of runway has the following runway condition]

Condition	Nov	Dec	Jan	Feb	Mar
Bare - dry	41.0	54.7	42.0	50.2	63.8
Bare - wet	39.7	17.0	10.5	17.5	23.4
Snow - loose	11.9	17.7	26.7	18.3	8.2
Snow - drift	1.7	2.3	2.8	0.2	0.3
Snow - compt	0.2	0.4	1.0	0.6	0.2
Ice - patch	4.2	6.7	13.5	11.9	2.8
Slush cover	1.2	0.7	1.2	1.0	1.3
Frost	0.1	0.5	2.5	0.3	0.0
Total hours*	1514	1580	1582	1445	1568

* Hours of data on which percentages are based

Percent of Time When Runway Condition BARE_DRY is in Range:

Condition	Nov	Dec	Jan	Feb	Mar
0 %	48.1	38.7	48.5	38.9	31.3
1 - 20 %	2.8	1.6	0.6	1.6	1.5
21 - 40 %	4.0	2.0	2.8	3.7	0.7
41 - 60 %	5.3	1.3	3.4	0.9	1.9
61 - 80 %	14.2	8.8	15.6	27.5	4.7
81 - 100 %	25.6	47.5	29.1	27.5	59.9
Total hours*	1514	1580	1582	1445	1567

Percent of Time When Runway Condition BARE_WET is in Range:

Condition	Nov	Dec	Jan	Feb	Mar
0 %	47.0	76.4	84.4	75.1	68.7
1 - 20 %	7.1	2.0	1.6	1.1	5.0
21 - 40 %	3.7	2.4	1.5	4.2	1.8
41 - 60 %	4.9	2.5	3.0	4.0	2.4
61 - 80 %	7.5	6.1	5.4	5.9	2.1
81 - 100 %	29.8	10.6	4.1	9.7	19.8
Total hours*	1514	1580	1582	1445	1567

Percent of Time When Runway Condition LOOSE_SNOW is in Range:

Condition	Nov	Dec	Jan	Feb	Mar
0 %	78.0	74.5	62.9	75.5	84.9
1 - 20 %	8.6	7.1	8.1	5.8	5.7
21 - 40 %	3.0	1.1	1.5	1.8	2.3
41 - 60 %	1.4	1.9	4.2	0.2	0.1
61 - 80 %	0.1	0.0	1.5	0.0	0.3
81 - 100 %	8.9	15.4	21.8	16.8	6.7
Total hours*	1514	1580	1582	1445	1567

Percent of Time When Runway Condition COMPACT_SN is in Range:

Condition	Nov	Dec	Jan	Feb	Mar
0 %	98.3	97.7	93.8	98.0	97.5
1 - 20 %	1.7	2.2	5.3	0.6	2.5
21 - 40 %	0.0	0.1	0.5	1.5	0.0
41 - 60 %	0.0	0.0	0.5	0.0	0.0
61 - 80 %	0.0	0.0	0.0	0.0	0.0
81 - 100 %	0.0	0.0	0.0	0.0	0.0
Total hours*	1514	1580	1582	1445	1567

Percent of Time When Runway Condition SNOW_DRIFT is in Range:

Condition	Nov	Dec	Jan	Feb	Mar
0 %	97.1	96.0	94.1	98.6	99.2
1 - 20 %	0.3	0.0	1.1	1.4	0.3
21 - 40 %	0.7	2.1	2.6	0.0	0.5
41 - 60 %	0.9	0.5	0.3	0.0	0.0
61 - 80 %	1.0	0.2	0.0	0.0	0.1
81 - 100 %	0.1	1.2	1.8	0.0	0.0
Total hours*	1514	1580	1582	1445	1567

Percent of Time When Runway Condition SLUSH is in Range:

Condition	Nov	Dec	Jan	Feb	Mar
0 %	97.5	98.9	97.8	97.1	98.3
1 - 20 %	0.7	0.0	0.4	1.7	0.2
21 - 40 %	1.1	0.3	0.7	0.5	0.2
41 - 60 %	0.1	0.3	0.4	0.0	0.0
61 - 80 %	0.0	0.1	0.0	0.3	0.2
81 - 100 %	0.6	0.3	0.7	0.3	1.1
Total hours*	1514	1580	1582	1445	1567

Percent of Time When Runway Condition FROST is in Range:

Condition	Nov	Dec	Jan	Feb	Mar
0 %	99.8	98.9	97.4	99.5	100.0
1 - 20 %	0.0	0.7	0.0	0.0	0.0
21 - 40 %	0.1	0.0	0.0	0.0	0.0
41 - 60 %	0.0	0.0	0.0	0.0	0.0
61 - 80 %	0.0	0.3	0.8	0.5	0.0
81 - 100 %	0.0	0.2	1.8	0.0	0.0
Total hours*	1514	1580	1582	1445	1567

```
Percent of Time When Runway Condition  ICE_PATCHS  is in Range:
---------------------------------------------------------------
Condition          Nov        Dec        Jan        Feb        Mar
---------------------------------------------------------------
   0    %         83.1       77.5       56.3       63.4       89.9
 1 - 20 %         10.9       12.7       29.0       27.3        5.4
21 - 40 %          3.3        4.7        3.2        2.6        2.4
41 - 60 %          1.5        1.9        4.0        0.2        1.0
61 - 80 %          0.2        0.8        1.7        1.3        0.6
81 - 100 %         1.0        2.5        5.7        5.3        0.7
-----------------------------------------------------------------
Total hours*      1514       1580       1582       1445       1567
-----------------------------------------------------------------

Average Percent of Time With Each Runway Condition
Given % Ice cover is in range:    0 ,    0
[Given that ice cover is in given range, the probability that any
given patch of runway is in the following condition is:]

---------------------------------------------------------------
Condition          Nov        Dec        Jan        Feb        Mar
---------------------------------------------------------------
Bare - dry       41.03      58.54      32.09      48.57      66.07
Bare - wet       41.48      15.99      12.09      20.47      23.21
Snow - loose     13.68      21.55      43.33      28.02       8.72
Snow - drift      2.06       2.22       4.80       0.33       0.27
Snow - compt      0.27       0.46       1.41       0.90       0.25
Ice - patchs      0.00       0.00       0.00       0.00       0.00
Slush cover       1.41       0.67       1.92       1.22       1.48
Frost             0.07       0.56       4.37       0.49       0.00
-----------------------------------------------------------------
Ice   0 - 0 % 1258.6     1224.2      891.3      915.2     1409.7 hrs
Percent          83.13      77.47      56.34      63.36      89.92
Total hours*      1514       1580       1582       1445       1568
-----------------------------------------------------------------

Average Percent of Time With Each Runway Condition
Given % Ice cover is in range:    1 ,   20
---------------------------------------------------------------
Condition          Nov        Dec        Jan        Feb        Mar
---------------------------------------------------------------
Bare - dry       54.31      65.13      77.33      69.56      59.08
Bare - wet       28.81      20.31       7.67      11.18      25.25
Snow - loose      4.36       0.61       1.37       1.38       5.89
Snow - drift      0.00       2.56       0.00       0.00       0.28
Snow - compt      0.00       0.04       0.83       0.00       0.00
Ice - patchs     12.52      11.10      12.63      17.59       9.49
Slush cover       0.00       0.00       0.17       0.28       0.00
Frost             0.00       0.24       0.00       0.00       0.00
-----------------------------------------------------------------
Ice  1 -20 %     165.1      200.2      458.0      394.7       84.8 hrs
Percent          10.90      12.67      28.95      27.33       5.41
Total hours*      1514       1580       1582       1445       1568
-----------------------------------------------------------------
```

Average Percent of Time With Each Runway Condition
Given % Ice cover is in range: 21 , 40

Condition	Nov	Dec	Jan	Feb	Mar
Bare - dry	20.86	21.61	26.27	14.53	38.56
Bare - wet	49.99	30.25	23.60	53.90	31.44
Snow - loose	0.00	9.62	16.47	0.00	0.00
Snow - drift	0.00	6.18	4.04	0.00	0.00
Snow - compt	0.00	0.24	0.33	0.00	0.00
Ice - patchs	29.15	29.12	29.29	29.95	30.00
Slush cover	0.00	2.97	0.00	1.63	0.00
Frost	0.00	0.00	0.00	0.00	0.00
Ice 21 -40 %	50.1	74.1	51.3	37.2	37.4 hrs
Percent	3.31	4.69	3.24	2.58	2.38
Total hours*	1514	1580	1582	1445	1568

Average Percent of Time With Each Runway Condition
Given % Ice cover is in range: 41 , 60

Condition	Nov	Dec	Jan	Feb	Mar
Bare - dry	19.68	5.60	9.00	0.00	9.33
Bare - wet	28.66	32.75	17.04	32.28	40.67
Snow - loose	0.00	10.57	23.71	11.11	0.00
Snow - drift	0.00	0.00	0.00	0.00	0.00
Snow - compt	0.00	0.46	0.00	0.00	0.00
Ice - patchs	51.67	50.61	50.25	50.00	50.00
Slush cover	0.00	0.00	0.00	6.60	0.00
Frost	0.00	0.00	0.00	0.00	0.00
Ice 41 -60 %	22.2	30.4	63.6	3.2	15.8 hrs
Percent	1.46	1.93	4.02	0.22	1.01
Total hours*	1514	1580	1582	1445	1568

Average Percent of Time With Each Runway Condition
Given % Ice cover is in range: 61 , 80

Condition	Nov	Dec	Jan	Feb	Mar
Bare - dry	0.00	0.00	19.93	5.97	30.00
Bare - wet	0.00	2.46	0.00	1.14	0.00
Snow - loose	30.00	20.56	4.54	9.11	0.00
Snow - drift	0.00	0.00	0.00	0.00	0.00
Snow - compt	0.00	0.00	0.00	0.00	0.00
Ice - patchs	70.00	76.98	71.82	78.86	70.00
Slush cover	0.00	0.00	3.70	4.92	0.00
Frost	0.00	0.00	0.00	0.00	0.00
Ice 61 -80 %	2.9	12.3	27.4	18.3	9.3 hrs
Percent	0.19	0.78	1.73	1.27	0.59
Total hours*	1514	1580	1582	1445	1568

Average Percent of Time With Each Runway Condition
Given % Ice cover is in range: 81 , 100

Condition	Nov	Dec	Jan	Feb	Mar
Bare - dry	0.00	0.00	0.00	0.00	2.00
Bare - wet	0.22	0.00	0.43	0.00	0.00
Snow - loose	0.99	3.42	5.43	0.00	0.00
Snow - drift	0.00	0.00	0.00	0.00	0.00
Snow - compt	0.00	0.00	0.00	0.00	0.00
Ice - patchs	98.79	96.58	99.17	100.00	98.00
Slush cover	0.00	0.00	0.00	0.00	0.00
Frost	0.00	0.00	0.00	0.00	0.00
Ice 81-100 %	15.1	38.9	90.3	75.8	10.7 hrs
Percent	1.00	2.46	5.71	5.25	0.69
Total hours*	1514	1580	1582	1445	1567

ANALYSIS OF TAPLEY READINGS UNDER GIVEN RUNWAY CONDITIONS

Distribution of Tapley Readings for Condition BARE_DRY

Tapley Reading	BARE_DRY < 51% No.	%	BARE_DRY >= 51% No.	%	Total No.	%
0.33	2	1.8	0	0.0	2	0.2
0.35	0	0.0	1	0.1	1	0.1
0.36	0	0.0	1	0.1	1	0.1
0.37	1	0.9	0	0.0	1	0.1
0.40	1	0.9	4	0.5	5	0.6
0.41	1	0.9	0	0.0	1	0.1
0.43	0	0.0	1	0.1	1	0.1
0.44	0	0.0	1	0.1	1	0.1
0.45	0	0.0	1	0.1	1	0.1
0.46	0	0.0	1	0.1	1	0.1
> 0.50	89	81.7	646	86.4	735	85.8
Total	109	12.7	748	87.3	857	

Distribution of Tapley Readings for Condition BARE_WET

Tapley Reading	BARE_WET < 51% No.	%	BARE_WET >= 51% No.	%	Total No.	%
0.35	3	1.9	0	0.0	3	0.6
0.36	1	0.6	0	0.0	1	0.2
0.39	1	0.6	0	0.0	1	0.2
0.40	1	0.6	1	0.3	2	0.4
0.44	2	1.3	0	0.0	2	0.4
0.45	1	0.6	2	0.5	3	0.6
> 0.50	141	89.8	345	90.1	486	90.0
Total	157	29.1	383	70.9	540	

ANALYSIS OF TAPLEY READINGS UNDER GIVEN RUNWAY CONDITIONS

Distribution of Tapley Readings for Condition BARE_DRY

Tapley	BARE_DRY < 51 %		BARE_DRY >= 51 %		Total	
Reading	No.	%	No.	%	No.	%
0.33	2	1.8	0	0.0	2	0.2
0.35	0	0.0	1	0.1	1	0.1
0.36	0	0.0	1	0.1	1	0.1
0.37	1	0.9	0	0.0	1	0.1
0.40	1	0.9	4	0.5	5	0.6
0.41	1	0.9	0	0.0	1	0.1
0.43	0	0.0	1	0.1	1	0.1
0.44	0	0.0	1	0.1	1	0.1
0.45	0	0.0	1	0.1	1	0.1
0.46	0	0.0	1	0.1	1	0.1
0.50	1	0.9	3	0.4	4	0.5
0.55	1	0.9	0	0.0	1	0.1
0.57	0	0.0	2	0.3	2	0.2
0.58	5	4.6	0	0.0	5	0.6
0.59	0	0.0	1	0.1	1	0.1
0.60	1	0.9	2	0.3	3	0.4
0.63	1	0.9	0	0.0	1	0.1
0.65	2	1.8	0	0.0	2	0.2
0.67	0	0.0	1	0.1	1	0.1
0.68	0	0.0	1	0.1	1	0.1
0.70	0	0.0	1	0.1	1	0.1
0.73	0	0.0	1	0.1	1	0.1
Not given	93	85.3	726	97.1	819	95.6
Total	109	12.7	748	87.3	857	

Distribution of Tapley Readings for Condition BARE_WET

Tapley Reading	BARE_WET < 51 % No.	%	BARE_WET >= 51 % No.	%	Total No.	%
0.35	3	1.9	0	0.0	3	0.6
0.36	1	0.6	0	0.0	1	0.2
0.39	1	0.6	0	0.0	1	0.2
0.40	1	0.6	1	0.3	2	0.4
0.44	2	1.3	0	0.0	2	0.4
0.45	1	0.6	2	0.5	3	0.6
0.50	0	0.0	2	0.5	2	0.4
0.52	1	0.6	0	0.0	1	0.2
0.55	0	0.0	2	0.5	2	0.4
0.57	0	0.0	2	0.5	2	0.4
0.60	0	0.0	5	1.3	5	0.9
0.63	0	0.0	1	0.3	1	0.2
0.65	0	0.0	2	0.5	2	0.4
0.67	1	0.6	0	0.0	1	0.2
0.70	0	0.0	4	1.0	4	0.7
0.75	0	0.0	1	0.3	1	0.2
0.77	0	0.0	1	0.3	1	0.2
Not given	146	93.0	360	94.0	506	93.7
Total	157	29.1	383	70.9	540	

Distribution of Tapley Readings for Condition LOOSE_SNOW

Tapley Reading	LOOSE_SNOW < 51 %		LOOSE_SNOW >= 51 %		Total	
	No.	%	No.	%	No.	%
0.10	1	0.6	0	0.0	1	0.2
0.13	1	0.6	0	0.0	1	0.2
0.15	0	0.0	2	0.7	2	0.4
0.16	0	0.0	1	0.3	1	0.2
0.20	0	0.0	6	2.0	6	1.2
0.22	0	0.0	1	0.3	1	0.2
0.23	0	0.0	1	0.3	1	0.2
0.24	0	0.0	3	1.0	3	0.6
0.25	0	0.0	6	2.0	6	1.2
0.26	0	0.0	2	0.7	2	0.4
0.27	0	0.0	2	0.7	2	0.4
0.28	0	0.0	2	0.7	2	0.4
0.29	1	0.6	3	1.0	4	0.8
0.30	1	0.6	21	6.9	22	4.6
0.32	2	1.1	3	1.0	5	1.0
0.33	2	1.1	6	2.0	8	1.7
0.34	2	1.1	4	1.3	6	1.2
0.35	4	2.2	17	5.6	21	4.3
0.36	1	0.6	2	0.7	3	0.6
0.37	0	0.0	8	2.6	8	1.7
0.38	0	0.0	6	2.0	6	1.2
0.39	1	0.6	5	1.7	6	1.2
0.40	6	3.3	15	5.0	21	4.3
0.41	1	0.6	3	1.0	4	0.8
0.42	1	0.6	2	0.7	3	0.6
0.43	0	0.0	3	1.0	3	0.6
0.44	1	0.6	5	1.7	6	1.2
0.45	3	1.7	7	2.3	10	2.1
0.46	1	0.6	4	1.3	5	1.0
0.47	0	0.0	5	1.7	5	1.0
0.48	1	0.6	0	0.0	1	0.2
0.49	0	0.0	1	0.3	1	0.2
0.50	4	2.2	6	2.0	10	2.1
0.51	0	0.0	3	1.0	3	0.6
0.55	0	0.0	5	1.7	5	1.0
0.56	0	0.0	2	0.7	2	0.4
0.57	1	0.6	2	0.7	3	0.6
0.59	0	0.0	1	0.3	1	0.2
0.60	1	0.6	7	2.3	8	1.7
0.62	0	0.0	2	0.7	2	0.4
0.63	0	0.0	1	0.3	1	0.2
0.65	0	0.0	5	1.7	5	1.0
0.66	0	0.0	1	0.3	1	0.2
0.67	0	0.0	1	0.3	1	0.2
0.68	0	0.0	2	0.7	2	0.4
0.70	1	0.6	3	1.0	4	0.8
Not given	143	79.4	116	38.3	259	53.6
Total	180	37.3	303	62.7	483	

```
Distribution of Tapley Readings for Condition COMPACT_SNOW
-------------------------------------------------------------------
Tapley      COMPACT_SN < 51 %   COMPACT_SN >= 51 %         Total
Reading       No.       %         No.        %         No.       %
-------------------------------------------------------------------
  0.29         1      2.2         0         0         1       2.2
  0.40         1      2.2         0         0         1       2.2
  0.60         1      2.2         0         0         1       2.2
  0.70         1      2.2         0         0         1       2.2
  0.73         1      2.2         0         0         1       2.2
Not given     40     88.9         0         0        40      88.9
-------------------------------------------------------------------
Total         45    100.0         0       0.0        45
--------------------------------------------------------------------
```

```
Distribution of Tapley Readings for Condition SNOW_DRIFT
-------------------------------------------------------------------
Tapley      SNOW_DRIFT < 51 %   SNOW_DRIFT >= 51 %         Total
Reading       No.       %         No.        %         No.       %
-------------------------------------------------------------------
  0.33         0      0.0         2      7.4          2       3.8
  0.34         1      3.8         3     11.1          4       7.5
  0.39         0      0.0         1      3.7          1       1.9
  0.40         1      3.8         1      3.7          2       3.8
  0.42         0      0.0         1      3.7          1       1.9
  0.44         1      3.8         0      0.0          1       1.9
  0.50         0      0.0         2      7.4          2       3.8
  0.56         0      0.0         1      3.7          1       1.9
  0.58         0      0.0         1      3.7          1       1.9
  0.60         2      7.7         0      0.0          2       3.8
Not given     21     80.8        15     55.6         36      67.9
-------------------------------------------------------------------
Total         26     49.1        27     50.9         53
--------------------------------------------------------------------
```

```
Distribution of Tapley Readings for Condition SLUSH
-------------------------------------------------------------------
Tapley      SLUSH < 51 %   SLUSH >= 51 %        Total
Reading       No.       %         No.        %         No.       %
-------------------------------------------------------------------
  0.27         0      0.0         1      4.0          1       1.8
  0.30         0      0.0         1      4.0          1       1.8
  0.32         1      3.3         0      0.0          1       1.8
  0.35         1      3.3         0      0.0          1       1.8
  0.42         0      0.0         1      4.0          1       1.8
  0.43         1      3.3         0      0.0          1       1.8
  0.55         1      3.3         0      0.0          1       1.8
Not given     26     86.7        22     88.0         48      87.3
-------------------------------------------------------------------
Total         30     54.5        25     45.5         55
--------------------------------------------------------------------
```

Distribution of Tapley Readings for Condition FROST

Tapley	FROST < 51 %		FROST >= 51 %		Total	
Reading	No.	%	No.	%	No.	%
0.30	0	0.0	1	7.7	1	5.3
0.33	0	0.0	1	7.7	1	5.3
0.35	0	0.0	1	7.7	1	5.3
0.38	0	0.0	1	7.7	1	5.3
0.40	0	0.0	1	7.7	1	5.3
0.47	0	0.0	1	7.7	1	5.3
0.48	0	0.0	1	7.7	1	5.3
0.55	0	0.0	1	7.7	1	5.3
0.61	0	0.0	1	7.7	1	5.3
0.62	0	0.0	1	7.7	1	5.3
Not given	6	100.0	3	23.1	9	47.4
Total	6	31.6	13	68.4	19	

Distribution of Tapley Readings for Condition ICE_PATCHS

Tapley Reading	ICE_PATCHS < 51 % No.	%	ICE_PATCHS >= 51 % No.	%	Total No.	%
0.10	1	0.3	4	4.7	5	1.1
0.13	1	0.3	0	0.0	1	0.2
0.16	1	0.3	0	0.0	1	0.2
0.20	0	0.0	3	3.5	3	0.7
0.22	0	0.0	1	1.2	1	0.2
0.23	0	0.0	1	1.2	1	0.2
0.24	0	0.0	1	1.2	1	0.2
0.25	0	0.0	2	2.3	2	0.4
0.26	0	0.0	1	1.2	1	0.2
0.27	0	0.0	1	1.2	1	0.2
0.28	0	0.0	1	1.2	1	0.2
0.29	1	0.3	4	4.7	5	1.1
0.30	1	0.3	1	1.2	2	0.4
0.31	0	0.0	1	1.2	1	0.2
0.32	0	0.0	2	2.3	2	0.4
0.33	0	0.0	2	2.3	2	0.4
0.34	5	1.4	2	2.3	7	1.6
0.35	1	0.3	7	8.1	8	1.8
0.36	1	0.3	2	2.3	3	0.7
0.37	1	0.3	3	3.5	4	0.9
0.38	0	0.0	4	4.7	4	0.9
0.39	2	0.6	1	1.2	3	0.7
0.40	4	1.1	1	1.2	5	1.1
0.41	0	0.0	5	5.8	5	1.1
0.42	0	0.0	2	2.3	2	0.4
0.43	1	0.3	4	4.7	5	1.1
0.44	0	0.0	2	2.3	2	0.4
0.45	2	0.6	1	1.2	3	0.7
0.47	0	0.0	1	1.2	1	0.2
0.50	5	1.4	1	1.2	6	1.3
0.51	0	0.0	2	2.3	2	0.4
0.52	1	0.3	1	1.2	2	0.4
0.55	1	0.3	1	1.2	2	0.4
0.57	2	0.6	1	1.2	3	0.7
0.58	4	1.1	0	0.0	4	0.9
0.59	1	0.3	0	0.0	1	0.2
0.60	5	1.4	0	0.0	5	1.1
0.63	1	0.3	1	1.2	2	0.4
0.67	1	0.3	0	0.0	1	0.2
0.68	1	0.3	0	0.0	1	0.2
0.70	3	0.8	0	0.0	3	0.7
0.77	1	0.3	0	0.0	1	0.2
Not given	315	86.8	19	22.1	334	74.4
Total	363	80.8	86	19.2	449	

ANALYSIS OF DEPTH OF CONTAMINANT GIVEN RUNWAY CONDITION

Distribution of Runway Condition Descriptors for LOOSE_SNOW

Condition Descriptor	LOOSE_SNOW < 51%		LOOSE_SNOW >= 51%		Total	
	No.	%	No.	%	No.	%
	77	42.8	31	10.2	108	22.4
.25"	2	1.1	0	0.0	2	0.4
1"	11	6.1	5	1.7	16	3.3
1.25"	0	0.0	1	0.3	1	0.2
1.5"	1	0.6	2	0.7	3	0.6
1/2"	12	6.7	18	5.9	30	6.2
1/4"	15	8.3	27	8.9	42	8.7
1/8"	0	0.0	7	2.3	7	1.4
10"	0	0.0	1	0.3	1	0.2
12"	1	0.6	7	2.3	8	1.7
18"	0	0.0	1	0.3	1	0.2
2"	5	2.8	8	2.6	13	2.7
2.5"	0	0.0	2	0.7	2	0.4
3"	8	4.4	5	1.7	13	2.7
3/4"	0	0.0	5	1.7	5	1.0
3/8"	1	0.6	5	1.7	6	1.2
4"	4	2.2	1	0.3	5	1.0
5"	1	0.6	0	0.0	1	0.2
6"	1	0.6	8	2.6	9	1.9
8"	0	0.0	10	3.3	10	2.1
TR-2"	0	0.0	2	0.7	2	0.4
TR.-3"	0	0.0	2	0.7	2	0.4
TRACE	41	22.8	153	50.5	194	40.2
TRACE-4	0	0.0	1	0.3	1	0.2
YTSVR	0	0.0	1	0.3	1	0.2
Total	180	37.3	303	62.7	483	

Distribution of Runway Condition Descriptors for SNOW_DRIFT

Condition	SNOW_DRIFT < 51%		SNOW_DRIFT >= 51%		Total	
Descriptor	No.	%	No.	%	No.	%
	9	34.6	3	11.1	12	22.6
1"	2	7.7	5	18.5	7	13.2
1.5"	0	0.0	3	11.1	3	5.7
1/2"	3	11.5	2	7.4	5	9.4
1/4"	4	15.4	0	0.0	4	7.5
1/8"	4	15.4	0	0.0	4	7.5
12"	1	3.8	0	0.0	1	1.9
2"	0	0.0	2	7.4	2	3.8
2.5"	0	0.0	1	3.7	1	1.9
3"	0	0.0	2	7.4	2	3.8
3/8"	1	3.8	1	3.7	2	3.8
4"	0	0.0	2	7.4	2	3.8
6"	1	3.8	1	3.7	2	3.8
8"	0	0.0	1	3.7	1	1.9
TRACE	1	3.8	4	14.8	5	9.4
Total	26	49.1	27	50.9	53	

Distribution of Runway Condition Descriptors for SLUSH

Condition	SLUSH < 51%		SLUSH >= 51%		Total	
Descriptor	No.	%	No.	%	No.	%
	13	43.3	2	8.0	15	27.3
1/2	1	3.3	0	0.0	1	1.8
1/2"	3	10.0	0	0.0	3	5.5
1/4"	1	3.3	4	16.0	5	9.1
1/8"	2	6.7	7	28.0	9	16.4
3"	2	6.7	1	4.0	3	5.5
4"	1	3.3	0	0.0	1	1.8
TRACE	7	23.3	11	44.0	18	32.7
Total	30	54.5	25	45.5	55	

RESULTS OF ANALYSES FOR HALIFAX RUNWAY 6/24

ANALYSIS OF FREQUENCY OF EACH RUNWAY CONDITION

Frequencies refer only to the period from 6 am to 11 pm. Runway conditions outside this time interval were not considered when determining the following percentages.

Average Percent of Time With Each Runway Condition
[probability that any given patch of runway has the following runway condition]

Condition	Nov	Dec	Jan	Feb	Mar
Bare - dry	58.9	51.5	37.3	34.4	56.3
Bare - wet	26.3	15.4	22.8	8.6	15.3
Snow - loose	5.3	10.7	15.2	20.9	8.3
Snow - drift	2.1	4.2	2.5	5.1	1.1
Snow - compt	0.6	1.8	2.3	6.1	0.6
Ice - patch	4.9	11.7	14.1	20.0	13.1
Slush cover	1.9	3.2	2.9	2.7	5.5
Frost	0.0	1.4	3.0	2.2	0.0
Total hours	1330	1154	1109	651	898

* Hours of data on which percentages are based

Note: As there were some extended time periods where no condition reports were available, the period for which a report was applicable was truncated to the following maximum number of days:

4 days if BARE_DRY >= 90%
2 days if BARE_WET >= 80% or BARE_DRY >=50%
1 day otherwise

ANALYSIS OF TAPLEY READINGS UNDER GIVEN RUNWAY CONDITIONS

Distribution of Tapley Readings for Condition BARE_DRY

Tapley Reading	BARE_DRY < 51 %		BARE_DRY >= 51 %		Total	
	No.	%	No.	%	No.	%
0.22	1	0.7	0	0.0	1	0.2
0.24	1	0.7	0	0.0	1	0.2
0.25	1	0.7	0	0.0	1	0.2
0.26	2	1.3	0	0.0	2	0.5
0.27	1	0.7	0	0.0	1	0.2
0.28	3	2.0	0	0.0	3	0.7
0.29	1	0.7	0	0.0	1	0.2
0.30	1	0.7	0	0.0	1	0.2
0.31	1	0.7	0	0.0	1	0.2
0.32	1	0.7	0	0.0	1	0.2
0.33	1	0.7	0	0.0	1	0.2
0.34	1	0.7	0	0.0	1	0.2
0.35	1	0.7	0	0.0	1	0.2
0.36	4	2.6	0	0.0	4	1.0
0.37	1	0.7	0	0.0	1	0.2
0.38	2	1.3	0	0.0	2	0.5
0.39	2	1.3	0	0.0	2	0.5
0.40	3	2.0	0	0.0	3	0.7
0.41	5	3.3	0	0.0	5	1.2
0.42	1	0.7	0	0.0	1	0.2
0.43	1	0.7	0	0.0	1	0.2
0.44	1	0.7	0	0.0	1	0.2
0.45	6	3.9	1	0.4	7	1.7
0.46	1	0.7	0	0.0	1	0.2
0.48	1	0.7	0	0.0	1	0.2
0.50	1	0.7	2	0.8	3	0.7
0.54	1	0.7	0	0.0	1	0.2
0.57	1	0.7	0	0.0	1	0.2
0.61	1	0.7	0	0.0	1	0.2
Not given	104	68.4	250	98.8	354	87.4
Total	152	37.5	253	62.5	405	

Distribution of Tapley Readings for Condition BARE_WET

Tapley	BARE_WET < 51 %		BARE_WET >= 51 %		Total	
Reading	No.	%	No.	%	No.	%
0.20	1	0.6	0	0.0	1	0.3
0.24	1	0.6	0	0.0	1	0.3
0.25	1	0.6	0	0.0	1	0.3
0.26	2	1.2	0	0.0	2	0.7
0.27	1	0.6	0	0.0	1	0.3
0.36	5	3.0	0	0.0	5	1.7
0.37	1	0.6	0	0.0	1	0.3
0.38	1	0.6	0	0.0	1	0.3
0.39	1	0.6	0	0.0	1	0.3
0.40	5	3.0	0	0.0	5	1.7
0.43	2	1.2	0	0.0	2	0.7
0.44	3	1.8	1	0.8	4	1.4
0.45	11	6.5	0	0.0	11	3.8
0.47	1	0.6	0	0.0	1	0.3
0.48	2	1.2	0	0.0	2	0.7
0.50	5	3.0	1	0.8	6	2.1
0.51	1	0.6	0	0.0	1	0.3
0.53	3	1.8	1	0.8	4	1.4
0.54	1	0.6	1	0.8	2	0.7
0.55	1	0.6	0	0.0	1	0.3
0.58	2	1.2	2	1.7	4	1.4
0.61	1	0.6	0	0.0	1	0.3
Not given	117	69.2	114	95.0	231	79.9
Total	169	58.5	120	41.5	289	

Distribution of Tapley Readings for Condition LOOSE_SNOW

Tapley	LOOSE_SNOW < 51 %		LOOSE_SNOW >= 51 %		Total	
Reading	No.	%	No.	%	No.	%
0.16	2	1.2	0	0.0	2	0.7
0.20	2	1.2	3	2.4	5	1.7
0.21	0	0.0	3	2.4	3	1.0
0.22	1	0.6	3	2.4	4	1.4
0.23	4	2.5	2	1.6	6	2.1
0.24	4	2.5	1	0.8	5	1.7
0.25	3	1.9	8	6.3	11	3.8
0.26	1	0.6	4	3.1	5	1.7
0.27	4	2.5	4	3.1	8	2.8
0.28	1	0.6	4	3.1	5	1.7
0.29	1	0.6	3	2.4	4	1.4
0.30	5	3.1	4	3.1	9	3.1
0.31	1	0.6	0	0.0	1	0.3
0.32	1	0.6	3	2.4	4	1.4
0.33	0	0.0	3	2.4	3	1.0
0.34	0	0.0	4	3.1	4	1.4
0.35	1	0.6	5	3.9	6	2.1
0.36	4	2.5	5	3.9	9	3.1
0.37	0	0.0	1	0.8	1	0.3
0.38	1	0.6	1	0.8	2	0.7
0.39	1	0.6	2	1.6	3	1.0
0.40	4	2.5	3	2.4	7	2.4
0.41	2	1.2	3	2.4	5	1.7
0.42	0	0.0	3	2.4	3	1.0
0.43	1	0.6	2	1.6	3	1.0
0.44	0	0.0	4	3.1	4	1.4
0.45	7	4.3	4	3.1	11	3.8
0.46	1	0.6	1	0.8	2	0.7
0.47	1	0.6	1	0.8	2	0.7
0.48	0	0.0	2	1.6	2	0.7
0.49	0	0.0	3	2.4	3	1.0
0.50	4	2.5	2	1.6	6	2.1
0.51	0	0.0	1	0.8	1	0.3
0.53	2	1.2	2	1.6	4	1.4
0.54	0	0.0	2	1.6	2	0.7
0.55	0	0.0	3	2.4	3	1.0
0.57	0	0.0	2	1.6	2	0.7
0.58	2	1.2	0	0.0	2	0.7
Not given	101	62.3	26	20.5	127	43.9
Total	162	56.1	127	43.9	289	

Distribution of Tapley Readings for Condition COMPACT_SNOW

Tapley Reading	COMPACT_SNOW < 51% No.	%	COMPACT_SNOW >= 51% No.	%	Total No.	%
0.18	1	0.8	0	0.0	1	0.8
0.19	1	0.8	0	0.0	1	0.8
0.22	1	0.8	0	0.0	1	0.8
0.23	1	0.8	0	0.0	1	0.8
0.25	4	3.1	0	0.0	4	3.1
0.26	1	0.8	0	0.0	1	0.8
0.27	2	1.6	0	0.0	2	1.5
0.28	2	1.6	0	0.0	2	1.5
0.29	1	0.8	0	0.0	1	0.8
0.30	3	2.3	0	0.0	3	2.3
0.31	1	0.8	0	0.0	1	0.8
0.32	2	1.6	0	0.0	2	1.5
0.33	1	0.8	0	0.0	1	0.8
0.36	2	1.6	0	0.0	2	1.5
0.40	2	1.6	0	0.0	2	1.5
0.41	1	0.8	0	0.0	1	0.8
0.45	4	3.1	0	0.0	4	3.1
0.47	1	0.8	0	0.0	1	0.8
0.48	1	0.8	0	0.0	1	0.8
0.50	1	0.8	0	0.0	1	0.8
0.54	2	1.6	0	0.0	2	1.5
Not given	93	72.7	3	100.0	96	73.3
Total	128	97.7	3	2.3	131	

Distribution of Tapley Readings for Condition SNOW_DRF

Tapley Reading	SNOW_DRF < 51 % No.	%	SNOW_DRF >= 51 % No.	%	Total No.	%
0.18	0	0.0	1	3.2	1	1.1
0.19	1	1.6	0	0.0	1	1.1
0.20	0	0.0	1	3.2	1	1.1
0.21	1	1.6	0	0.0	1	1.1
0.22	0	0.0	1	3.2	1	1.1
0.23	1	1.6	0	0.0	1	1.1
0.24	1	1.6	3	9.7	4	4.2
0.25	6	9.4	1	3.2	7	7.4
0.26	1	1.6	0	0.0	1	1.1
0.27	1	1.6	1	3.2	2	2.1
0.28	1	1.6	1	3.2	2	2.1
0.29	3	4.7	1	3.2	4	4.2
0.30	1	1.6	3	9.7	4	4.2
0.31	1	1.6	1	3.2	2	2.1
0.32	7	10.9	1	3.2	8	8.4
0.33	2	3.1	0	0.0	2	2.1
0.34	1	1.6	0	0.0	1	1.1
0.35	1	1.6	0	0.0	1	1.1
0.39	0	0.0	1	3.2	1	1.1
0.40	2	3.1	0	0.0	2	2.1
0.41	0	0.0	1	3.2	1	1.1
0.50	1	1.6	0	0.0	1	1.1
Not given	32	50.0	14	45.2	46	48.4
Total	64	67.4	31	32.6	95	

Distribution of Tapley Readings for Condition SLUSH

Tapley	SLUSH < 51 %		SLUSH >= 51 %		Total	
Reading	No.	%	No.	%	No.	%
0.22	0	0.0	2	6.7	2	3.0
0.24	1	2.8	0	0.0	1	1.5
0.25	0	0.0	2	6.7	2	3.0
0.26	0	0.0	1	3.3	1	1.5
0.27	1	2.8	0	0.0	1	1.5
0.28	0	0.0	1	3.3	1	1.5
0.29	0	0.0	2	6.7	2	3.0
0.30	0	0.0	2	6.7	2	3.0
0.34	0	0.0	1	3.3	1	1.5
0.35	1	2.8	1	3.3	2	3.0
0.38	0	0.0	1	3.3	1	1.5
0.40	1	2.8	0	0.0	1	1.5
0.41	1	2.8	0	0.0	1	1.5
0.44	1	2.8	0	0.0	1	1.5
0.45	0	0.0	1	3.3	1	1.5
0.47	1	2.8	0	0.0	1	1.5
0.48	0	0.0	1	3.3	1	1.5
0.50	1	2.8	1	3.3	2	3.0
Not given	28	77.8	14	46.7	42	63.6
Total	36	54.5	30	45.5	66	

Distribution of Tapley Readings for Condition FROST

Tapley	FROST < 51 %		FROST >= 51 %		Total	
Reading	No.	%	No.	%	No.	%
0.19	1	4.5	0	0.0	1	3.1
0.28	1	4.5	0	0.0	1	3.1
0.33	1	4.5	0	0.0	1	3.1
0.36	1	4.5	1	10.0	2	6.3
0.38	1	4.5	0	0.0	1	3.1
0.41	0	0.0	1	10.0	1	3.1
0.44	0	0.0	1	10.0	1	3.1
0.45	0	0.0	1	10.0	1	3.1
0.47	1	4.5	0	0.0	1	3.1
0.48	0	0.0	1	10.0	1	3.1
0.54	0	0.0	1	10.0	1	3.1
Not given	16	72.7	4	40.0	20	62.5
Total	22	68.8	10	31.3	32	

Distribution of Tapley Readings for Condition ICE_PATCHES

Tapley	ICE_PATCHES < 51%		ICE_PATCHES >= 51%		Total	
Reading	No.	%	No.	%	No.	%
0.16	0	0.0	2	1.5	2	0.6
0.17	0	0.0	1	0.8	1	0.3
0.18	0	0.0	1	0.8	1	0.3
0.19	0	0.0	2	1.5	2	0.6
0.20	2	0.9	5	3.8	7	2.0
0.21	0	0.0	1	0.8	1	0.3
0.22	0	0.0	7	5.4	7	2.0
0.23	2	0.9	4	3.1	6	1.7
0.24	2	0.9	3	2.3	5	1.4
0.25	1	0.5	9	6.9	10	2.8
0.26	1	0.5	8	6.2	9	2.6
0.27	4	1.8	4	3.1	8	2.3
0.28	1	0.5	6	4.6	7	2.0
0.29	1	0.5	3	2.3	4	1.1
0.30	4	1.8	7	5.4	11	3.1
0.31	1	0.5	2	1.5	3	0.9
0.32	4	1.8	3	2.3	7	2.0
0.33	0	0.0	5	3.8	5	1.4
0.34	0	0.0	1	0.8	1	0.3
0.35	3	1.4	2	1.5	5	1.4
0.36	7	3.2	5	3.8	12	3.4
0.37	0	0.0	2	1.5	2	0.6
0.38	1	0.5	2	1.5	3	0.9
0.39	2	0.9	0	0.0	2	0.6
0.40	2	0.9	3	2.3	5	1.4
0.41	0	0.0	3	2.3	3	0.9
0.43	1	0.5	1	0.8	2	0.6
0.44	1	0.5	1	0.8	2	0.6
0.45	7	3.2	4	3.1	11	3.1
0.46	1	0.5	0	0.0	1	0.3
0.47	1	0.5	0	0.0	1	0.3
0.48	1	0.5	0	0.0	1	0.3
0.50	4	1.8	3	2.3	7	2.0
0.51	0	0.0	1	0.8	1	0.3
0.53	2	0.9	0	0.0	2	0.6
0.54	1	0.5	0	0.0	1	0.3
0.58	3	1.4	0	0.0	3	0.9
0.61	1	0.5	0	0.0	1	0.3
Not given	161	72.5	29	22.3	190	54.0
Total	222	63.1	130	36.9	352	

ANALYSIS OF DEPTH OF CONTAMINANT GIVEN RUNWAY CONDITIONS

Distribution of Runway Contamination Depth for LOOSE_SNOW

Depth Inches	LOOSE_SNOW < 51%		LOOSE _SNOW >= 51%		Total	
	No.	%	No.	%	No.	%
Not given	62	38.3	19	15.0	81	28.0
TRACE	60	37.0	58	45.7	118	40.8
.125	4	2.5	11	8.7	15	5.2
.25	6	3.7	10	7.9	16	5.5
.5	7	4.3	9	7.1	16	5.5
.75	1	0.6	1	0.8	2	0.7
0.5	0	0.0	1	0.8	1	0.3
01	0	0.0	1	0.8	1	0.3
1	12	7.4	2	1.6	14	4.8
1.0	2	1.2	2	1.6	4	1.4
1.5	2	1.2	1	0.8	3	1.0
12	0	0.0	3	2.4	3	1.0
2	4	2.5	4	3.1	8	2.8
2.0	1	0.6	0	0.0	1	0.3
2.5	0	0.0	1	0.8	1	0.3
4	1	0.6	3	2.4	4	1.4
5	0	0.0	1	0.8	1	0.3
Total	162	56.1	127	43.9	289	

Distribution of Runway Contamination Depth for SNOW_DRF

Depth Inches	SNOW_DRF < 51 No.	%	SNOW_DRF >= 51 No.	%	Total No.	%
Not given	9	14.1	3	9.7	12	12.6
TRACE	4	6.3	1	3.2	5	5.3
.125	6	9.4	0	0.0	6	6.3
.25	15	23.4	1	3.2	16	16.8
.5	7	10.9	5	16.1	12	12.6
.75	5	7.8	1	3.2	6	6.3
1	7	10.9	1	3.2	8	8.4
1.0	3	4.7	1	3.2	4	4.2
1.25	0	0.0	1	3.2	1	1.1
1.5	2	3.1	3	9.7	5	5.3
10	0	0.0	1	3.2	1	1.1
12	1	1.6	1	3.2	2	2.1
2	2	3.1	2	6.5	4	4.2
3	1	1.6	4	12.9	5	5.3
3.0	1	1.6	0	0.0	1	1.1
3.5	0	0.0	1	3.2	1	1.1
4	0	0.0	3	9.7	3	3.2
4.0	1	1.6	1	3.2	2	2.1
6	0	0.0	1	3.2	1	1.1
Total	64	67.4	31	32.6	95	

Distribution of Runway Contamination Depth for SLUSH

Depth Inches	SLUSH < 51 No.	%	SLUSH >= 51 No.	%	Total No.	%
Not given	12	33.3	4	13.3	16	24.2
TRACE	14	38.9	8	26.7	22	33.3
.125	2	5.6	7	23.3	9	13.6
.25	1	2.8	3	10.0	4	6.1
.5	2	5.6	3	10.0	5	7.6
.75	1	2.8	2	6.7	3	4.5
1	1	2.8	1	3.3	2	3.0
1.0	1	2.8	0	0.0	1	1.5
1.5	0	0.0	1	3.3	1	1.5
2	1	2.8	0	0.0	1	1.5
2.0	0	0.0	1	3.3	1	1.5
3	1	2.8	0	0.0	1	1.5
Total	36	54.5	30	45.5	66	

APPENDIX G

EXTRACTS FROM ICAO ANNEX 15

INTERNATIONAL STANDARDS
AND RECOMMENDED PRACTICES

AERONAUTICAL INFORMATION SERVICES

ANNEX 15

TO THE CONVENTION ON INTERNATIONAL CIVIL AVIATION

SEVENTH EDITION — JULY 1987

This edition incorporates all amendments adopted by the Council prior to 7 March 1987 and supersedes, on 22 October 1987, all previous editions of Annex 15.

For information regarding the applicability of the Standards and Recommended Practices, *see* Foreword.

INTERNATIONAL CIVIL AVIATION ORGANIZATION

AMENDMENTS

The issue of amendments is announced regularly in the *ICAO Bulletin* and in the monthly *Supplement to the Catalogue of ICAO Publications*, which holders of this publication should consult. The space below is provided to keep a record of such amendments.

RECORD OF AMENDMENTS AND CORRIGENDA

AMENDMENTS			
No.	Date Applicable	Date entered	Entered by
1-26	Incorporated in this Edition		

CORRIGENDA			
No.	Date of issue	Date entered	Entered by

APPENDIX 2. SNOWTAM FORMAT

(See 5.5.4 of this Annex)

(COM heading)	(PRIORITY INDICATOR)	(ADDRESSES)		≪≡
	(DATE AND TIME OF FILING)	(ORIGINATOR'S INDICATOR)		≪≡
(Abbreviated heading)	(SWAA* SERIAL NUMBER) S W * *	(LOCATION INDICATOR)	DATE/TIME OF OBSERVATION	(OPTIONAL GROUP) ≪≡(

SNOWTAM	(Serial number) →

(AERODROME LOCATION INDICATOR)	A) →
(DATE/TIME OF OBSERVATION *(Time of completion of measurement in UTC)*)	B) →
(RUNWAY DESIGNATORS)	C) →
(CLEARED RUNWAY LENGTH, IF LESS THAN PUBLISHED LENGTH *(m)*)	D) →
(CLEARED RUNWAY WIDTH, IF LESS THAN PUBLISHED WIDTH *(m; if offset left or right of centre line add "L" or "R")*)	E) →
(DEPOSITS OVER TOTAL RUNWAY LENGTH *(Observed on each third of the runway, starting from threshold having the lower runway designation number)* NIL — CLEAR AND DRY 1 — DAMP 2 — WET or water patches 3 — RIME OR FROST COVERED *(depth normally less than 1 mm)* 4 — DRY SNOW 5 — WET SNOW 6 — SLUSH 7 — ICE 8 — COMPACTED OR ROLLED SNOW 9 — FROZEN RUTS OR RIDGES)	F) →
(MEAN DEPTH *(mm)* FOR EACH THIRD OF TOTAL RUNWAY LENGTH)	G) →
(BRAKING ACTION ON EACH THIRD OF RUNWAY AND MEASURING EQUIPMENT	H) →

MEASURED OR CALCULATED COEFFICIENT	*or*	ESTIMATED BRAKING ACTION	
0.40 and above		GOOD	— 5
0.39 to 0.36		MEDIUM/GOOD	— 4
0.35 to 0.30		MEDIUM	— 3
0.29 to 0.26		MEDIUM/POOR	— 2
0.25 and below		POOR	— 1
9 - unreliable		UNRELIABLE	— 9

(When quoting a measured coefficient use the observed two figures, followed by the abbreviation of the measuring equipment used. When quoting an estimate use single digits))

(CRITICAL SNOWBANKS *(If present, insert height (cm)/distance from the edge of runway (m) followed by "L", "R" or "LR" if applicable)*)	J) →
(RUNWAY LIGHTS *(If obscured, insert "YES" followed by "L", "R" or both "LR" if applicable)*)	K) →
(FURTHER CLEARANCE *(If planned, insert length (m)/width (m) to be cleared or if to full dimensions, insert "TOTAL")*)	L) →
(FURTHER CLEARANCE EXPECTED TO BE COMPLETED BY ... *(UTC)*)	M) →
(TAXIWAY *(If no appropriate taxiway is available, insert "NO")*)	N) →
(TAXIWAY SNOWBANKS *(If more than 60 cm, insert "YES" followed by distance apart, m)*)	P) →
(APRON *(If unusable insert "NO")*)	R) →
(NEXT PLANNED OBSERVATION/MEASUREMENT IS FOR) *(month/day/hour in UTC)*	S) →
(PLAIN LANGUAGE REMARKS *(Including contaminant coverage and other operationally significant information, e.g. sanding, deicing)*)	T))≪≡

NOTES
1. *Enter ICAO nationality letters as given in ICAO Doc 7910, Part 2
2. Information on other runways, repeat from C to P
3. Words in brackets ( ) not to be transmitted

SIGNATURE OF ORIGINATOR *(not for transmission)*

GUIDANCE FOR THE COMPLETION OF THE SNOWTAM FORMAT

1. *General*

a) When reporting on two or three runways, repeat items C to P inclusive.

b) Items together with their indicator must be dropped completely, where no information is to be included.

c) Metric units must be used and the unit of measurement not reported.

d) The maximum validity of SNOWTAM is 24 hours. New SNOWTAM must be issued whenever there is a significant change in conditions. The following changes relating to runway conditions are considered as significant:

1) a change in the coefficient of friction of about 0.05;
2) changes in depth of deposit greater than the following: 20 mm for dry snow, 10 mm for wet snow, 3 mm for slush;
3) a change in the available length or width of a runway of 10 per cent or more;
4) any change in the type of deposit or extent of coverage which requires reclassification in Items F or T of the SNOWTAM;
5) when critical snow banks exist on one or both sides of the runway, any change in the height or distance from centre line;
6) any change in the conspicuity of runway lighting caused by obscuring of the lights; and
7) any other conditions known to be significant according to experience or local circumstances.

e) The abbreviated heading "TTAAiiii CCCC MMYYGGgg (BBB)" is included to facilitate the automatic processing of SNOWTAM messages in computer data banks. The explanation of these symbols is:

TT = data designator for SNOWTAM = SW;
AA = geographical designator for States, e.g. LF = FRANCE, EG = United Kingdom (see *Location Indicators* (Doc 7910), Part 2, Index to Nationality Letters for Location Indicators);
iiii = SNOWTAM serial number in a four-figure group;
CCCC = four-letter location indicator of the aerodrome to which the SNOWTAM refers (see *Location Indicators* (Doc 7910);
MMYYGGgg = date/time of observation/measurement, whereby:
  MM = month, e.g. January = 01, December = 12
  YY = day of the month
  GGgg = time in hours (GG) and minutes (gg) UTC;
(BBB) = optional group for:
  Correction to SNOWTAM message previously disseminated with the same serial number = COR.

Note.— Brackets in (BBB) are used to indicate that this group is optional.

Example: Abbreviated heading of SNOWTAM No. 149 from Zurich, measurement/observation of 7 November at 0620 UTC:

SWLS0149 LSZH 11070620

2. *Item A* — Aerodrome location indicator (four-letter location indicator).

3. *Item B* — Eight-figure date/time group — giving time of observation as month, day, hour and minute in UTC; this item must always be completed.

4. *Item C* — Lower runway designator number.

5. *Item D* — Cleared runway length in metres, if less than published length (see Item T on reporting on part of runway not cleared).

6. *Item E* — Cleared runway width in metres, if less than published width; if offset left or right of centre line add "L" or "R", as viewed from the threshold having the lower runway designation number.

7. *Item F* — Deposit over total runway length as explained in SNOWTAM Format. Suitable combinations of these numbers may be used to indicate varying conditions over runway segments. If more than one deposit is present on the same portion of the runway, they should be reported in sequence from the top to the bottom. Drifts, depths of deposit appreciably greater than the average values or other significant characteristics of the deposits may be reported under Item T in plain language.

Note.— Definitions for the various types of snow are given at the end of this Appendix.

8. *Item G* — Mean depth in millimetres deposit for each third of total runway length, or "XX" if not measurable or operationally not significant; the assessment to be made to an accuracy of 20 mm for dry snow, 10 mm for wet snow and 3 mm for slush.

9. *Item H* — Braking conditions on each third of the runway and measuring equipment. Measured or calculated coefficient (two digits) or, if not available, estimated braking action (single digit) in the order from the threshold having the lower runway designation number. Insert a code 9 when surface conditions or available measuring equipment do not permit a reliable braking action measurement to be made. Use the following abbreviations to indicate the type of measuring equipment used:

DBV	Diagonal Braked Vehicle	SKH	Skiddometer (high pressure tire)
JBD	James Brake Decelerometer	SKL	Skiddometer (low pressure tire)
MUM	Mu-meter	TAP	Tapley-meter
SFT	Friction Tester		

If other equipment used specify in plain language.

10. *Item J* — Critical snowbanks. If present insert height in centimetres and distance from edge of runway in metres, followed by Left ("L") or Right ("R") side or both sides ("LR"), as viewed from the threshold having the lower runway designation number.

11. *Item K* — If runway lights are obscured insert "YES" followed by "L", "R" or both "LR" as viewed from the threshold having the lower runway designation number.

12. *Item L* — When further clearance will be undertaken, enter length and width of runway or "TOTAL" if runway will be cleared to full dimensions.

13. *Item M* — Enter the anticipated time of completion in UTC.

14. *Item N* — The code for Item F may be used to describe taxiway conditions; enter "NO" if no taxiways serving the associated runway are available.

15. *Item P* — If applicable, enter "YES" followed by the lateral distance in metres.

16. *Item R* — The code for Item F may be used to describe apron conditions; enter "NO" if apron unusable.

17. *Item S* — Enter the anticipated time of next observation/measurement in UTC.

18. *Item T* — Describe in plain language any operationally significant information but always report on length of uncleared runway (Item D) and extent of runway contamination (Item F) for each third of the runway (if appropriate) in accordance with the following scale:

Runway contamination — 10% — if less than 10% of runway contaminated
Runway contamination — 25% — if 11-25% of runway contaminated
Runway contamination — 50% — if 26-50% of runway contaminated
Runway contamination — 100% — if 51-100% of runway contaminated.

EXAMPLE OF COMPLETED SNOWTAM FORMAT

```
GG EHAMZQZX EDDFZQZX EKCHZQZX
070645 LSZHYNYX
SWLS0149 LSZH 11070620
SNOWTAM 0149
A) LSZH  B)  11070620 C)  02 D) . . . P)
                      C)  09 D) . . . P)
                      C)  12 D) . . . P)
R) NO    S)  11070920 T)  DEICING.
```

Definitions of the various types of snow

Slush. Water-saturated snow which with a heel-and-toe slap-down motion against the ground will be displaced with a splatter; specific gravity: 0.5 up to 0.8.

Note.— Combinations of ice, snow and or standing water may, especially when rain, rain and snow, or snow is falling, produce substances with specific gravities in excess of 0.8. These substances, due to their high water ice content, will have a transparent rather than a cloudy appearance and, at the higher specific gravities, will be readily distinguishable from slush.

Snow (on the ground).

a) *Dry snow.* Snow which can be blown if loose or, if compacted by hand, will fall apart again upon release; specific gravity: up to but not including 0.35.

b) *Wet snow.* Snow which, if compacted by hand, will stick together and tend to or form a snowball; specific gravity: 0.35 up to but not including 0.5.

c) *Compacted snow.* Snow which has been compressed into a solid mass that resists further compression and will hold together or break up into lumps if picked up; specific gravity: 0.5 and over.

APPENDIX H

EXTRACT FROM ICAO ANNEX 14

ATTACHMENT A

TO

ANNEX 14, AERODROMES

OF

INTERNATIONAL STANDARDS

AND RECOMMENDED PRACTICES

INTERNATIONAL STANDARDS
AND RECOMMENDED PRACTICES

AERODROMES

ANNEX 14

TO THE CONVENTION ON INTERNATIONAL CIVIL AVIATION

EIGHTH EDITION — MARCH 1983

This edition incorporates all amendments adopted by the Council prior to 23 November 1982 and supersedes, on 24 November 1983, all previous editions of Annex 14.

For information regarding the applicability of the Standards and Recommended Practices, *see* Chapter 1, 1.2 and Foreword.

INTERNATIONAL CIVIL AVIATION ORGANIZATION

AMENDMENTS

The issue of amendments is announced regularly in the *ICAO Bulletin* and in the monthly *Supplement to the Catalogue of ICAO Publications*, which holders of this publication should consult. The space below is provided to keep a record of such amendments.

RECORD OF AMENDMENTS AND CORRIGENDA

AMENDMENTS			
No.	Date Applicable	Date entered	Entered by
1-38	Incorporated in this edition		

CORRIGENDA			
No.	Date of issue	Date entered	Entered by
1	1/10/84	Incorporated in this edition	

the LDA for approaches made to that threshold; all declared distances for operations in the reciprocal direction are unaffected.

3.6 Figures A-1 (B) through A-1 (D) illustrate a runway provided with a clearway or a stopway or having a displaced threshold. Where more than one of these features exist, then more than one of the declared distances will be modified — but the modification will follow the same principle illustrated. An example showing a situation where all these features exist is shown in Figure A-1 (E).

3.7 A suggested format for providing information on declared distances is given in Figure A-1 (F). If a runway direction cannot be used for take-off or landing, or both, because it is operationally forbidden, then this should be declared and the words "not usable" or the abbreviation "NU" entered.

4. Slopes on a runway

4.1 Distance between slope changes

4.1.1 The following example illustrates how the distance between slope changes is to be determined (see Figure A-2):

D for a runway where the code number is 3 should be at least:

$$15\,000\,(|x-y| + |y-z|)\ \text{m}$$

$|x-y|$ being the absolute numerical value of $x-y$
$|y-z|$ being the absolute numerical value of $y-z$

Assuming $x = +0.01$
$y = -0.005$
$z = +0.005$
then $|x-y| = 0.015$
$|y-z| = 0.01$

To comply with the specifications, D should be not less than:

$$15\,000\,(0.015 + 0.01)\ \text{m},$$

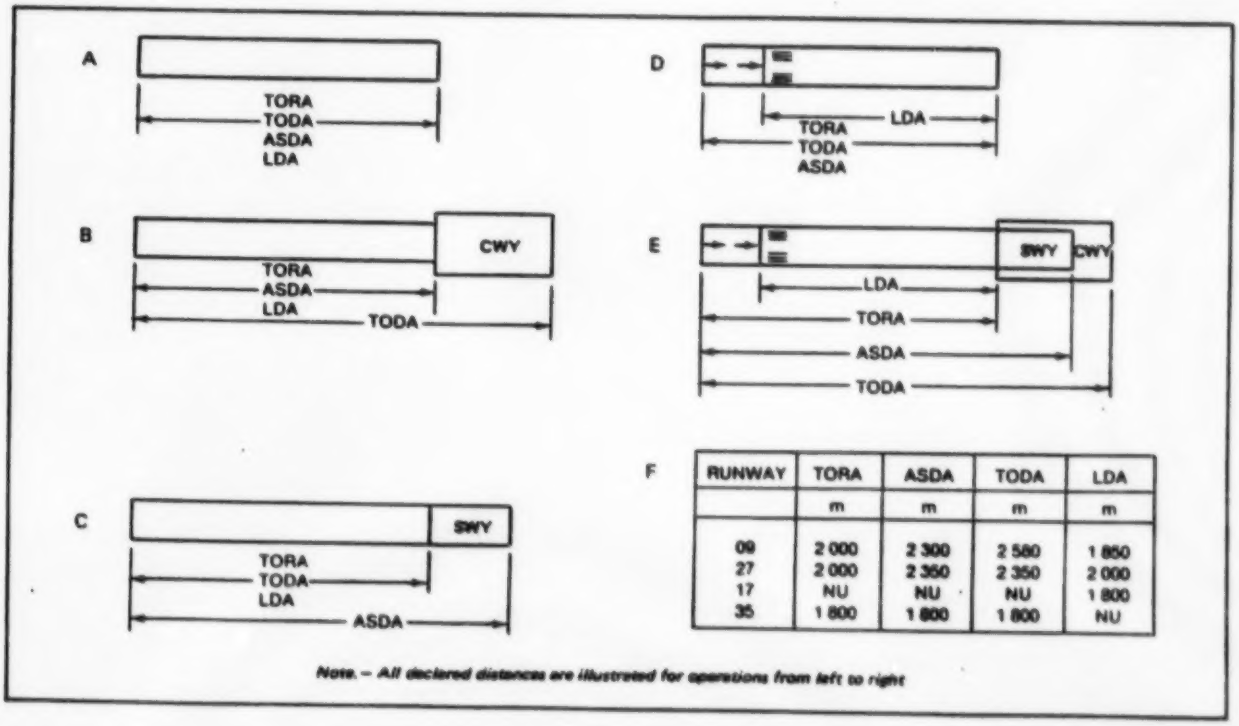
that is, $15\,000 \times 0.025 = 375$ m

4.2 Consideration of longitudinal and transverse slopes

4.2.1 When a runway is planned that will combine the extreme values for the slopes and changes in slope permitted under Chapter 3, 3.1.11 to 3.1.17, a study should be made to ensure that the resulting surface profile will not hamper the operation of aeroplanes.

4.3 Slope changes before runways

4.3.1 In order to accommodate aeroplanes making auto-coupled approaches and automatic landings (irrespective of



RUNWAY	TORA	ASDA	TODA	LDA
	m	m	m	m
09	2 000	2 300	2 580	1 850
27	2 000	2 350	2 350	2 000
17	NU	NU	NU	1 800
35	1 800	1 800	1 800	NU

Note. — All declared distances are illustrated for operations from left to right

Figure A-1. Illustration of declared distances

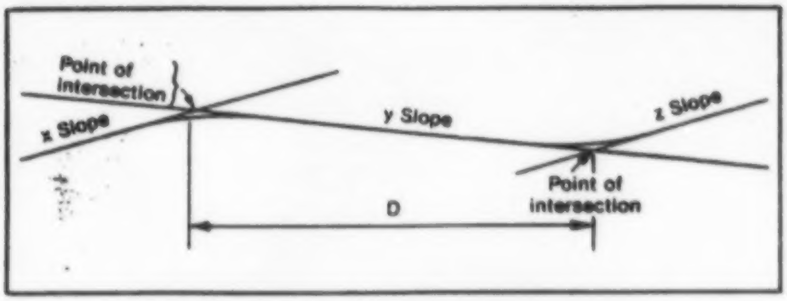


Figure A-2. Profile on centre line of runway

weather conditions), it is desirable that slope changes be avoided, or kept to a minimum, on an area symmetrical about the extended runway centre line approximately 60 m wide and 300 m long before the threshold of a precision approach runway. This is desirable because these aeroplanes are equipped with a radio altimeter for final height and flare guidance, and when the aeroplane is above the terrain immediately prior to the threshold, the radio altimeter will begin to provide information to the automatic pilot for auto-flare. Where slope changes cannot be avoided, the rate of change between two consecutive slopes should not exceed 2 per cent per 30 m.

5. Runway surface evenness

5.1 In adopting tolerances for runway surface irregularities, the following standard of construction is achievable for short distances of 3 m and conforms to good engineering practice:

> Except across the crown of a camber or across drainage channels, the finished surface of the wearing course is to be of such regularity that, when tested with a 3 m straight-edge placed anywhere in any direction on the surface, there is no deviation greater than 3 mm between the bottom of the straight-edge and the surface of the pavement anywhere along the straight edge.

5.2 Caution should also be exercised when inserting runway lights or drainage grilles in runway surfaces to ensure that adequate smoothness of the surface is maintained.

5.3 The operation of aircraft and differential settlement of surface foundations will eventually lead to increases in surface irregularities. Small deviations in the above tolerances will not seriously hamper aircraft operations. In general, isolated irregularities of the order of 2.5 cm to 3 cm over a 45 m distance are tolerable. Exact information of the maximum acceptable deviation cannot be given, as it varies with the type and speed of an aircraft.

5.4 Deformation of the runway with time may also increase the possibility of the formation of water pools. Pools as shallow as approximately 3 mm in depth, particularly if they are located where they are likely to be encountered at high speed by landing aeroplanes, can induce aquaplaning, which can then be sustained on a wet runway by a much shallower depth of water. Improved guidance regarding the significant length and depth of pools relative to aquaplaning is the subject of further research. It is, of course, especially necessary to prevent pools from forming whenever there is a possibility that they might become frozen.

6. Measuring and expressing braking action on snow- and ice-covered runways

6.1 There is an operational need for reliable and uniform information on runway braking action on ice- and snow-covered runways. Good indications of braking action can be obtained by test devices; however, further experience is required to correlate the results obtained by such equipment with aircraft performance, owing to the many variables involved, such as: aircraft mass, speed, braking mechanism, tire and undercarriage characteristics.

6.2 Braking action should be measured if a runway is covered wholly or partly by snow, ice or frost, and repeated as conditions change. Braking action measurements and/or assessments on surfaces other than runways should be made when an unsatisfactory braking action can be expected on such surfaces.

6.3 The measurement of the surface friction appears to provide the best basis for determining braking action. The value of surface friction should be the maximum value which occurs when a wheel is slipping but still rolling. Various methods may be used to measure the friction. Operational consideration will generally determine the most suitable method to be used at a particular aerodrome. As there is an operational need for uniformity in the method of assessing and reporting runway friction, the measurement should preferably be made with equipment which provides continuous measuring of the maximum friction along the entire runway. In the *Airport Services Manual*, Part 2, measuring techniques are described and information is given on limitations of methods and precautions to be observed.

6.4 A chart, based on results of tests conducted on selected ice- or snow-covered surfaces, showing the correlation between certain braking test devices on ice- or snow-covered surfaces is presented in the *Airport Services Manual*, Part 2.

6.5 The braking conditions of a runway should be expressed as "braking action information" in terms of the measured/calculated friction coefficient μ. Specific numerical μ values are necessarily related to the design and construction of each test device as well as to the surface being measured and the speed employed.

6.6 The table below with associated descriptive terms was developed from experience in compacted snow and ice with one type of decelerometer and one type of continuous measuring device at fixed speeds, and should not therefore be taken to be absolute values applicable in all conditions. If the surface is affected by snow or ice and the braking action is reported as "good", pilots should not expect to find conditions as good as on a clean dry runway (where the available friction may well be greater than that needed in any case). The value "good" is a comparative value and is intended to mean that aeroplanes should not experience directional control or braking difficulties, especially when landing.

Measured/ calculated coefficient	*Estimated braking action*	*Code*
0.40 and above	Good	5
0.39 to 0.36	Medium to good	4
0.35 to 0.30	Medium	3
0.29 to 0.26	Medium to poor	2
0.25 and below	Poor	1

6.7 It has been found necessary to provide braking action information for each third of a runway. The thirds are called A, B and C. For the purpose of reporting information to aeronautical service units, section A is always the section associated with the lower runway designation number. When giving landing information to a pilot before landing, the sections are however referred to as first, second or third part of the runway. The first part always means the first third of the runway as seen in the direction of landing. Braking action tests are made along two lines parallel to the runway, i.e. along a line on each side of the centre line approximately 3 m or that distance from the centre line at which most operations take place. The objective of the tests is to determine the mean friction value for sections A, B and C. In cases where a continuous measuring device is used, the mean values are obtained from the friction values recorded for each section. Corresponding mean friction values obtained by a braked vehicle should be calculated on the basis of at least nine braking tests along each of the two test lines over the usable length of the runway. The distance between each test point should be approximately 10 per cent of the usable length of the runway. If it is decided that a single test line on one side of the runway centre line gives adequate coverage of the runway, then it follows that each third of the runway should have three tests carried out on it. Test results and calculated mean friction values are entered in a special form (see *Airport Services Manual*, Part 2).

Note.— Where applicable, figures for stopway friction value should also be made available on request.

6.8 A continuous measuring device (e.g. Skiddometer, Surface Friction Tester or Mu-meter), or a diagonal braked vehicle, can be used for measuring the friction values for compacted snow- and ice-covered runways. A decelerometer (e.g. Tapley Meter or James Brake Decelerometer) may be used on certain surface conditions, e.g. compacted snow, ice and very thin layers of dry snow. Other measuring devices can be used, provided they have been correlated with at least one of the types mentioned above. A decelerometer or diagonal braked vehicle should not be used in loose snow or slush, as they can give misleading friction values. Other vehicles can also give misleading friction values unless otherwise proven.

6.9 The *Airport Services Manual*, Part 2 provides guidance on the uniform use of test equipment to achieve compatible test results and other information on removal of surface contamination and improvement of braking action.

7. Determination of friction characteristics of wet runways

7.1 The friction of a wet runway should be measured to:

a) provide periodic calibrations of the value of the wet runway surface friction (2.6);

b) assess the slipperiness of runways when wet (9.4.4);

c) determine the effect on friction when drainage characteristics are poor (9.4.5); and

d) determine the friction of runways that become slippery under unusual conditions (2.9.7).

7.2 Runways should be calibrated when first constructed or after resurfacing to determine the wet runway surface friction characteristic. Although it is recognized that friction reduces with use, calibration identifies the friction of the relatively long central portion of the runway that is uncontaminated by rubber deposits from aircraft operations and is therefore of operational value. Calibration tests should be made on clean surfaces. If it is not possible to clean a surface before testing, then for purposes of preparing an initial report a test could be made on a portion of clean surface in the central part of the runway. For uniformity and to permit comparison with other runways, the tests should be made with a uniform water depth, and therefore the use of the test equipment with a self-wetting device is necessary.

7.3 Friction tests of existing surface conditions should be taken periodically in order to identify runways with low friction when wet. A State should define what minimum friction it considers acceptable before a runway is classified as slippery when wet and publish this value in the State's aeronautical information publication (AIP). When the friction of a runway is found to be below this reported value, then such information should be promulgated by NOTAM and appropriate action initiated to improve the friction. Friction measurements should be taken at intervals that will ensure identification of runways in need of maintenance or special surface treatment before the condition becomes serious. The time interval between measurements will depend on factors such as: aircraft type and frequency of usage, climatic conditions, pavement type, and pavement service and maintenance requirements. As is the case for calibration tests, these tests should be made with a uniform water depth, and the use of test equipment with a self-wetting device is required.

7.4 When it is suspected that the braking characteristics of a runway may be reduced because drainage, owing to inadequate slopes or depressions, is poor, then an additional test should be made, but this time under natural conditions representative of a local rain. This test differs from the previous one in that water depths in the poorly cleared areas are normally greater in a local rain condition. The test results are thus more apt to identify problems of aquaplaning than the previous test. If circumstances do not permit tests to be conducted during natural conditions representative of a rain, then this condition may be simulated.

7.5 Even when the friction has been found to be above the level set by the State to define a slippery runway, it may be known that under unusual conditions, such as after a long dry period, the runway may have become slippery. When such a condition is known to exist, then a special test should be made as soon as it is suspected that the runway may have become slippery.

7.6 When the results of any of the measurements identified in 7.2 through 7.5 indicate that only a particular portion of a runway surface is slippery, then action to promulgate this information and, if appropriate, take corrective action is equally important.

7.7 When conducting friction tests on wet runways, it is important to note that, unlike compacted snow and ice conditions, in which there is very limited variation of braking action with speed, a wet runway usually produces a marked drop in friction with an increase in speed. However, as the speed increases, the rate at which the braking action is reduced becomes less. Among the factors affecting the braking friction coefficient between the tire and the runway surface, texture is particularly important. If the runway has an open texture allowing the water to escape either through the tire tread pattern or beneath the tire, then the friction value will be less affected by speed. Conversely, a smooth surface will experience a larger drop in friction with increase in speed. Accordingly, when testing runways to determine their friction and whether maintenance action is necessary to improve it, a speed high enough to reveal these friction/speed variations should be used.

7.8 The Annex recommends that States specify a friction level below which maintenance action should be taken and for reporting when runways may be slippery when wet. Experience with different measuring devices shows the following criteria in use in some States for specifying the friction characteristics of new runway surfaces and establishing maintenance levels:

Test equipment	Design objective for new runway surface	Maintenance level	Test water depth (mm)	Test speed (km/h)
(1)	(2)	(3)	(4)	(5)
Mu-meter —				
method 1	0.7	0.5	1.0	65
method 2	0.65	0.45	0.5	130
Skiddometer and Friction Tester	0.5	0.35	1.0	130 with high-pressure tire
	0.6	0.4	1.0	95
	0.7	0.5	1.0	65
Stradographe	0.6	0.35	1.0	65

The values in columns (2) and (3) are averaged values representative of the runway or significant portions thereof.

In countries where the Skiddometer and Friction Tester are used, it is also considered desirable to test braking action at more than one speed and test speeds of 130, 95 and 65 km/h are used. If tests are to be performed at a unique speed, a speed of 130 km/h is considered preferable.

7.9 The measurements specified in this section may not directly correlate with aircraft performance. Research work indicates that reasonable correlation between friction measurements and the friction available for aircraft exists provided the measured values are referenced to a common base line.

8. Strips

8.1 Shoulders

8.1.1 The shoulder of a runway or stopway should be prepared or constructed so as to minimize any hazard to an aeroplane running off the runway or stopway. Some guidance is given in the following paragraphs on certain special problems which may arise, and on the further question of measures to avoid the ingestion of loose stones or other objects by turbine engines.

8.1.2 In some cases, the bearing strength of the natural ground in the strip may be sufficient, without special preparation, to meet the requirements for shoulders. Where special preparation is necessary, the method used will depend on local soil conditions and the mass of the aeroplanes the runway is intended to serve. Soil tests will help in determining the best method of improvement (e.g. drainage, stabilization, surfacing, light paving).

8.1.3 Attention should also be paid when designing shoulders to prevent the ingestion of stones or other objects by turbine engines. Similar considerations apply here to those which are discussed for the margins of taxiways in the *Aerodrome Design Manual*, Part 2, both as to the special measures which may be necessary and as to the distance over which such special measures, if required, should be taken.

8.1.4 Where shoulders have been treated specially, either to provide the required bearing strength or to prevent the presence of stones or debris, difficulties may arise because of a lack of visual contrast between the runway surface and that of the adjacent strip. This difficulty can be overcome either by providing a good visual contrast in the surfacing of the runway or strip, or by providing a runway side stripe marking.

8.2 Objects on strips

8.2.1 Within the general area of the strip adjacent to the runway, measures should be taken to prevent an aeroplane's wheel, when sinking into the ground, from striking a hard vertical face. Special problems may arise for runway light fittings or other objects mounted in the strip or at the intersection with a taxiway or another runway. In the case of construction, such as runways or taxiways, where the surface must also be flush with the strip surface, a vertical face can be eliminated by chamfering from the top of the construction to